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LUNAR EXPLORER

A Space Flight Simulator

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LUNAR EXPLORER

A Space Flight Simulator

ELECTRIC TRANSIT

22 August 2046

To: Colonization

From: Director, Sele

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LUNAR EXPLORER

APPLE

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LUNAR EXPLORER

A Space Flight Simulator

ELECTRIC TRANSIT

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A portion of the program and some of the training exercises contained in this manual were previously published by EduWare Services, Inc. under the title *Tranquility Base*.

10 9 8 7 6 5 4 3 2 1

Cover design: COY, Los Angeles
Cover illustration: Mark McCandlish

ELECTRIC TRANSIT
501 Marin Street
Suite 116
Thousand Oaks, CA 91360

805/373-1960

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We gratefully acknowledge the National Aeronautics and Space Administration for its publications on the space program. Much of the information contained in this manual is drawn from NASA Space Colonization studies.

We extend our appreciation to the following people who contributed their time and talents to this project: L. Roberts for designing, developing, and implementing the program; Dr. Wesley T. Huntress for verifying scientific accuracy; David Mullich for enhancing the Apple version of the program; and Pam Pollack for designing and developing the final form of this manual.

INTRODUCTION

You have been sent out to rescue an astronaut stranded at the emergency landing pad. Lift-off was perfect, all control panel readouts are on target, trajectory is on course. And then. . .

as you approach the emergency landing pad and spot your fellow pilot, you pitch your LLV too late and overshoot the pad. Desperate, you look at the fuel gauge and calculate. Only enough fuel for one pass and return! Will you try again and risk a cold death in the lunar wastes? Or can you cut your maneuvers fine enough to accomplish your mission and return to Tranquility Base alive?

Men will face just such situtations when the dream of living in space becomes a reality. And though science fiction has been the traditional arena in which space colonization has been explored, today's scientific community is engaged in serious discussions about permanent space habitats and extraterrestrial manufacturing facilities. *Lunar Explorer: A Space Flight Simulator* presents one view of what life in space might be like and teaches one set of skills necessary for extraterrestrial survival.

Lunar Explorer is a training system consisting of a Lunar Landing Vehicle (LLV) simulator contained on the disk and the written material contained in this manual. Thorough training requires that both portions of the system be used together. Once you have mastered the LLV controls you can investigate the Moon on your own. Explore rilles and craters; find the Apollo 11 landing site; observe the Earth rise over the Moon's horizon. Or set out on a mission to collect ore canisters left on the Moon's surface by mobile mining teams.

Acceptance letter in hand, you are about to become a part of Training Group A for Lunar Landing Vehicle Pilots. Your training will include a preliminary period during which you will use an LLV simulator. This simulator and the required exercises (detailed in Pilot Training Manual) should be mastered before any real flying time is logged.

Lunar Explorer's LLV simulator provides a real-time recreation of flight from orbit to Moon landing from the pilot's point of view. Using either keyboard or joystick controls, you will learn to master the forces of gravity and inertial motion as you maneuver the LLV over hazardous lunar terrain. All flights begin at the Tranquility Base landing pad, in close approach to the lunar base, or in lunar orbit. The LLV simulator exposes you to the real dangers of inaccurate navigation, inefficient fuel consumption, and incorrect maneuvering. If fuel is consumed before reaching your destination, you may be doomed to orbit the Moon forever or you may suddenly terminate your career in a fatal crash.

The cockpit window presents the lunar landscape from your perspective. Solid color 3-D graphics depict important environmental features such as the lunar bases and refueling stations, craters, and constellations.

The *Lunar Explorer* manual is divided into three sections: an introduction to the Space Colonization Project; the Pilot Training Manual (to be used in conjunction with the software); and the Appendixes. The first section describes the DAKOTA Space Habitat in translunar space, the Lunar Mining Facility at Tranquility Base on the lunar surface, and the relationships within and between this biosystem and Earth. This information, gathered from several NASA sources, creates a context in which to understand and appreciate your role as an LLV pilot.

The second section, Pilot Training Manual, describes the LLV and details the exercises that should be mastered before you attempt any solo flight experience. The Pilot Training Manual is designed to be used in conjunction with the *Lunar Explorer* software. Each of the eight exercises trains you in a specific piloting skill. Once you are confident of your ability to control the LLV, you can take solo flights, chart your own investigations of the Moon, and try your hand at the cargo run mission.

The Appendixes gather together relevant collateral material: a complete glossary of terms, a section on Newtonian physics, geological information on the Moon, astronaut qualifications, suggestions for using *Lunar Explorer* in the classroom, and a list of sources and additional readings. Pay special attention to Appendix C: The Physics of Space Flight. To truly understand your LLV and the forces that influence piloting maneuvers, these universal laws must become second nature to you.

For those pilot candidates anxious to experience the LLV simulator before reading this manual, *Lunar Explorer* includes a Craft Control Summary card that describes starting procedures, summarizes keyboard and joystick controls, and explains control panel messages.

SPACE COLONIZATION PROJECT

- Overview
- The DAKOTA Space Habitat
  - Physical Structure
    - Residential Area
    - Agricultural Area
    - Waste Processing Area
  - Industry
  - Sociological Aspects
- The Transportation System
- Tranquility Base Mining Facility
  - Mining and Processing
  - Mass Launcher
  - Mass Catcher
- Conclusion

This information has been compiled for the purposes of providing DAKOTA visitors and settlers with an overview of the Space Colonization Project and presenting an introduction to the Space Habitat/Lunar Mining Colony system. Read this material carefully before reaching your destination.

OVERVIEW

The DAKOTA Space Habitat and its Lunar Mining Facility at Tranquility Base actively use the environment of space for economic development and scientific progress. DAKOTA, the initial community in the Space Colonization Project, is a first step in establishing man's foothold in space.

The center of the Colonization Project system is the DAKOTA where 10,000 people work, raise families, and live out normal human lives. The wheel-like structure in which they live orbits the Earth in the same orbit as the Moon, a position that is equidistant from both Earth and Moon. This location is called the Langrangian libration point L_5.

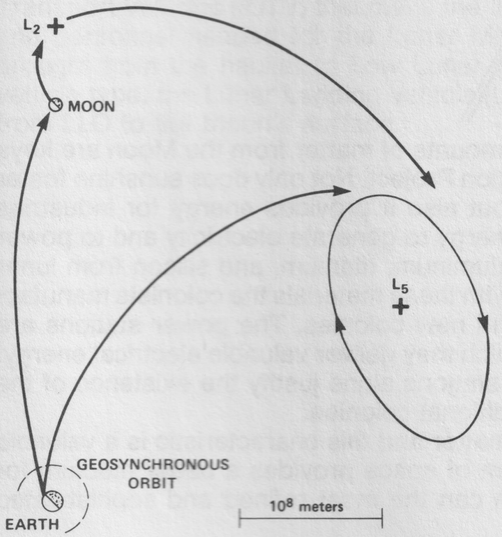


Figure 1: *Paths through space for space colonization*

The DAKOTA consists of a tube bent into a wheel and connected by six large spokes to a central hub. The spacecraft dock, nicknamed the North Pole by residents, is located on the north side of the hub. The spokes provide entry and exit to the living and agricultural areas in the tubular region (torus). To simulate Earth's normal gravity the torus rotates at 1 revolution per minute (rpm) around the central hub. A large stationary mirror, used to direct sunlight into the Habitat, is suspended directly over the hub. To the south of the DAKOTA's hub is a radiator panel, the fabrication facility, and a solar furnace. They are connected to the rest of the Habitat by a transport tube.

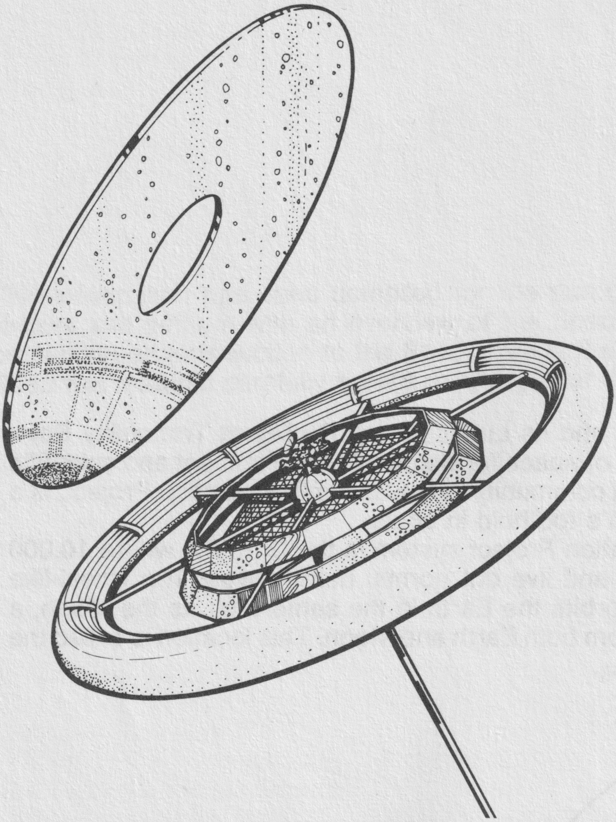


Figure 2: *DAKOTA at Langrangian point L_5*

Abundant solar energy and large amounts of matter from the Moon are keys to the success of the Space Colonization Project. Not only does sunshine foster agriculture of unusual productivity, but also it provides energy for industries needed by the Colony. Using solar energy to generate electricity and to power solar furnaces, the colonists refine aluminum, titanium, and silicon from lunar ores shipped from Tranquility Base. With these materials the colonists manufacture satellite solar power stations and new colonies. The power stations are placed in orbit around the Earth to which they deliver valuable electrical energy. The economic value of these power stations alone justify the existence of the DAKOTA and the construction of additional colonies.

Space is extraordinarily empty of matter and this characteristic is a valuable resource in its own right. The vacuum of space provides a better medium for developing industrial processes than can the most refined and sophisticated laboratory equipment on Earth.

The Moon, the Earth's natural satellite, is a convenient source of raw materials for the DAKOTA. It is near the Habitat and the gravitational well surrounding the Moon is only 1/22 as deep as that of the Earth. This shallow well makes it easier and less expensive to lift material out of the Moon's gravitational field. Lunar rock is a source of light metals, aluminum, titanium, and iron for construction, oxygen for respiration and rocket fuel, and silicon for glass. (There are trace amounts of hydrogen and carbon on the Moon, though not enough to supply the Colony.) The Moon's resources, supplemented by small amounts of particular elements from Earth, supply all the elements necessary to sustain human life and technology at the DAKOTA.

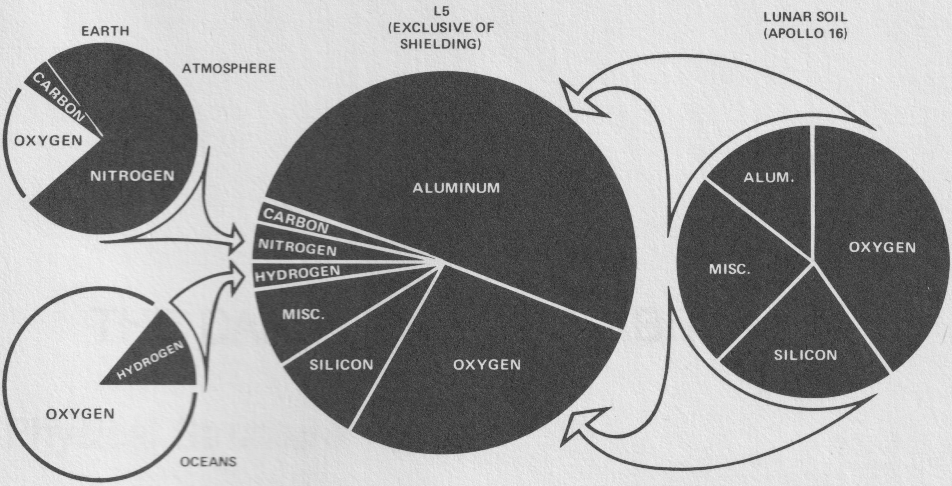


Figure 3: *Sources of Materials pie chart of resources and their locations relative to L_5*

The DAKOTA's transportation requirements are extensive and complex. Heavy Lift Launch Vehicles (HLLV) carry cargo and personnel from Earth to Low Earth Orbit (LEO). Here, cargo and passengers are transferred to Inter-Orbital Transport Vehicles (IOTV) that make the trip from LEO to DAKOTA at L_5. Cargo and personnel headed for the Lunar Mining Facility at Tranquility Base are brought from the habitat to Low Lunar Orbit (LLO) by another IOTV. A third vehicle type, the Lunar Landing Vehicle (LLV) ferries equipment and personnel from LLO to the Moon's surface.

THE DAKOTA SPACE HABITAT

Physical Structure

The DAKOTA appears as a giant wheel, 1790 meters (m) in diameter, with six 15-m-diameter spokes connecting the rim (torus) to a central hub. A rough "outer tire," built of rubble from the Moon, shields the Habitat from radiation. The hub, 830 m from the torus, is the crossroads for the DAKOTA complex. The 130 m-diameter torus provides the space for housing, agriculture, community activities, and light industry. The spokes accommodate elevators, power cables, and heat exchange pipes between the torus and the hub. Several thousand commuters pass through these access routes each day to and from their work in the fabrication sphere or outside the Habitat.

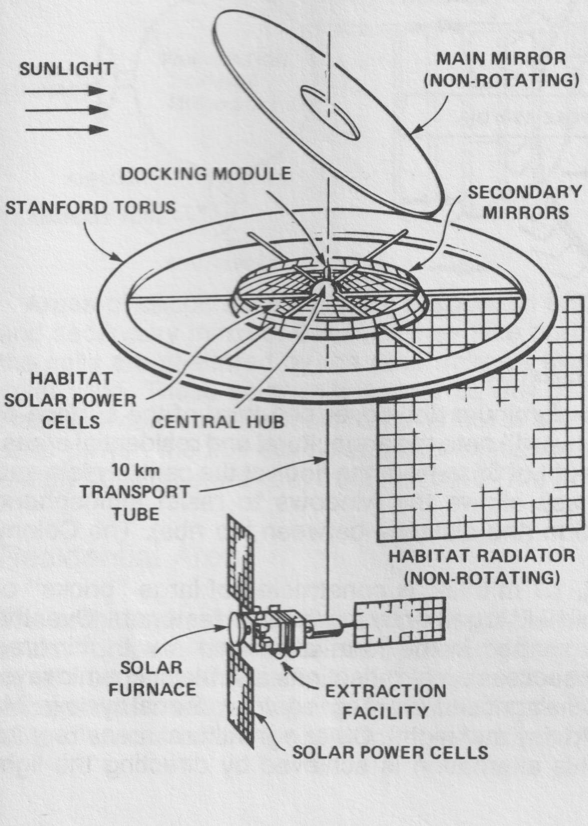
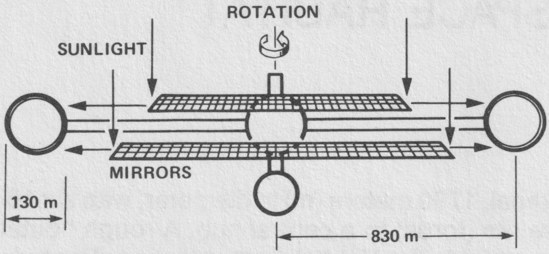


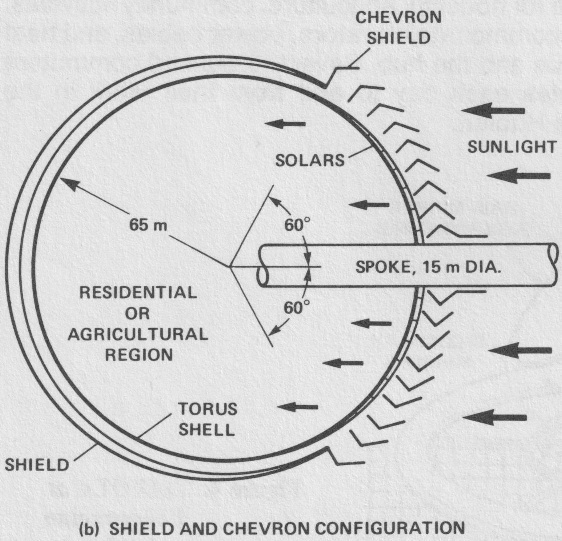
Figure 4: *DAKOTA at Langrangian point L_5*

A large mirror that hangs above the DAKOTA is the Colony's source of light and power. This mirror is inclined at 45 degrees to the axis of rotation and directs sunlight onto another set of mirrors which, in turn, reflect it into the interior of the Habitat's tube through a third set of mirrors. The louvered design of this final set admits light to the DAKOTA while acting as a baffle to stop cosmic radiation.

Two-thirds of the torus surface is covered by aluminum plates with a skin thickness of 2.1 centimeters (cm). This shell can resist loads of 530,000 tons (t) in addition to 50 kiloPascals (kPa) of atmospheric pressure and the centrifugal forces of its own mass.



(a) SECONDARY MIRROR CONFIGURATION



(b) SHIELD AND CHEVRON CONFIGURATION

Figure 5: *Cross section of the torus*

Glass windows mounted on aluminum ribs cover one-third of the surface of the torus and admit light "downward" onto the agricultural and residential areas. All windows are placed at a height of 65 m from the floor of the central plain and are 2.8 cm thick. This thickness allows the windows to resist atmospheric pressure across a span of 0.5 m (the distance between the ribs). The Colony contains 48,000 t of glass.

The cosmic radiation shield, 1.7 m thick, is constructed of large "bricks" of fused undifferentiated lunar soil held together by mechanical fasteners. Over the window regions the shield is shaped in the form of chevrons with mirrored surfaces which pass light by a succession of reflections and block cosmic rays.

The residential areas and some agricultural areas require a diurnal cycle (a 24-hour period divided equally into day and night). Other agricultural areas require continuous solar radiation. This alternation is achieved by directing the light

away from certain windows to obtain darkness and by concentrating the light from several mirrors onto other windows.

The DAKOTA's fabrication sphere is 100 m in diameter and is located on the south side of the central hub. It houses facilities for manufacturing, assembly, and construction. To one side of the fabrication sphere is a 200 megawatt (mw) solar power plant and furnace used to power this facility. At the opposite side of the fabrication sphere is a 490,000 sq m expanse of the Habitat's radiator with its edge toward the Sun. It disperses into space waste heat delivered to it by a complex of heat exchangers that pass through the Habitat's spokes. Like the main mirror, the fabrication sphere and radiator do not rotate.

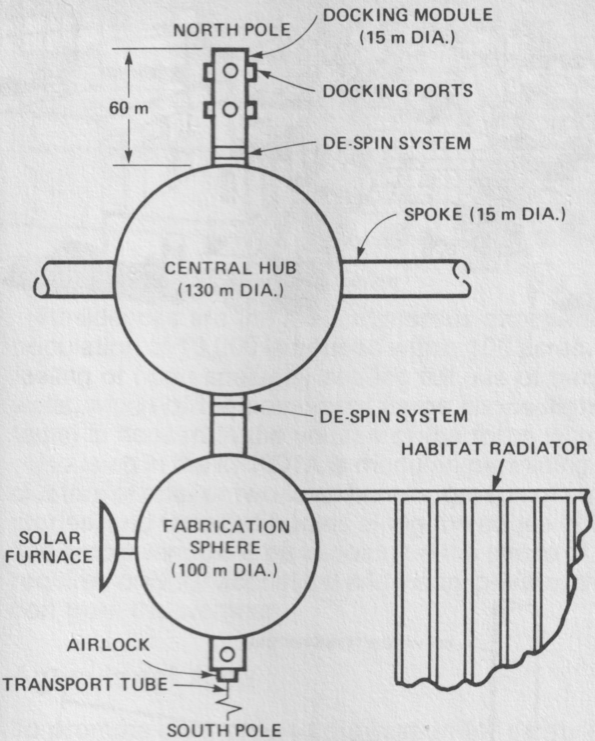


Figure 6: *Hub configuration*

Areas of silicon solar cells are suspended between the spokes, central hub, and secondary mirrors. Because they face northward toward the main mirror, the cells are sheltered by the other mirrors from the degrading effects of the solar wind. These solar cells supply 50 mw of electric power required by the Habitat. If control of the main mirror is lost or some other accident causes loss of solar power, the 200 mw solar power station at the extraction facility (approximately 10 kilometers (km) from he DAKOTA's South Pole) would supply power.

Residential Area

The architecture of the city has been carefully designed to maintain a human scale. This scale is emphasized by the long lines of sight, the frequent clusters of small fruit trees and parks, and the sense of openness produced by the broad expanse of sunlight coming from overhead. This central plain runs the full circumference of the torus along the middle of the tube.

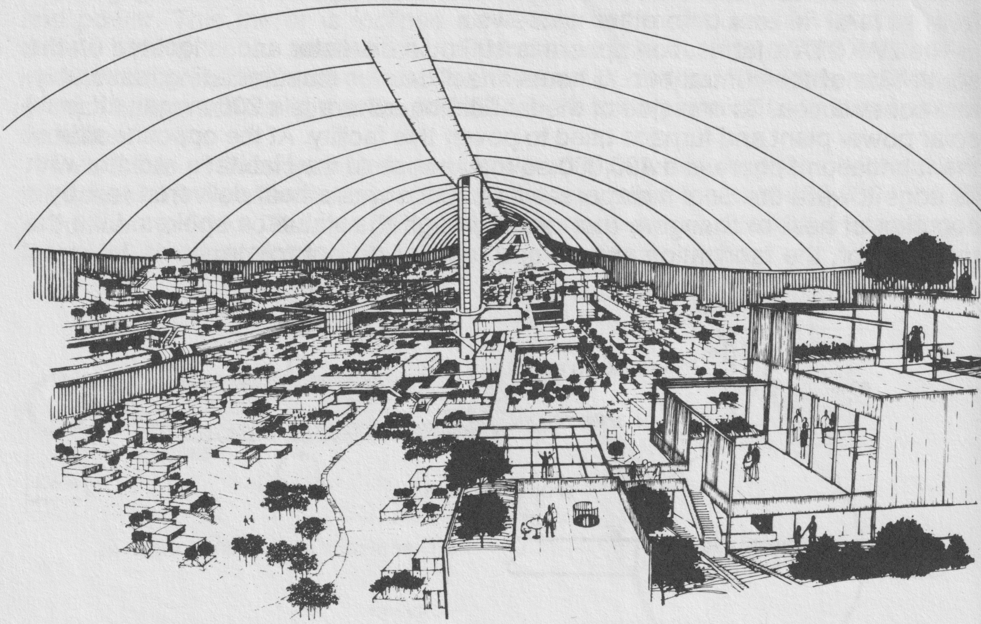


Figure 7: *View of DAKOTA's interior*

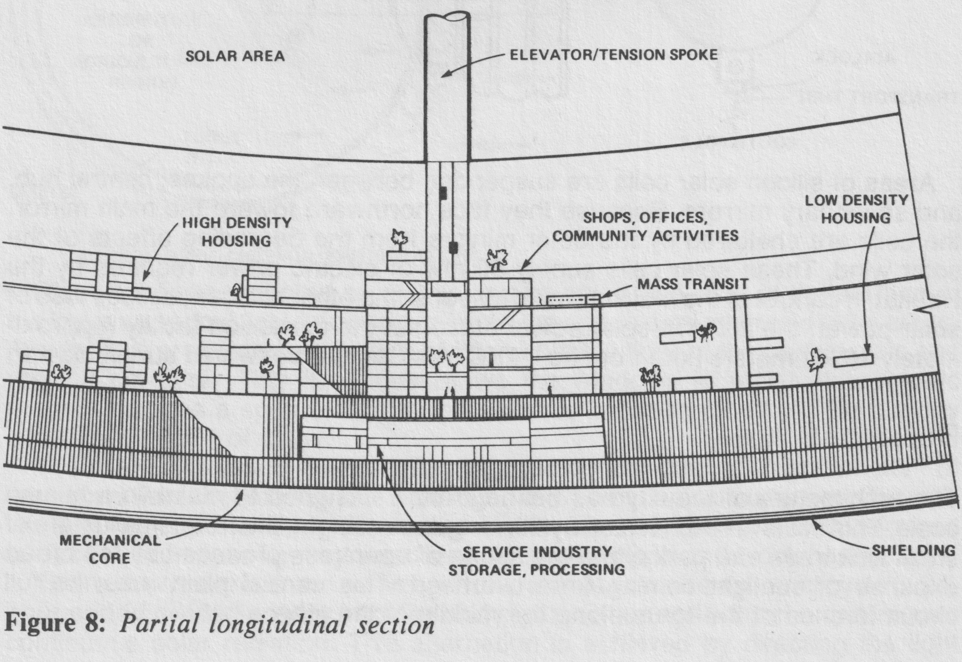


Figure 8: *Partial longitudinal section*

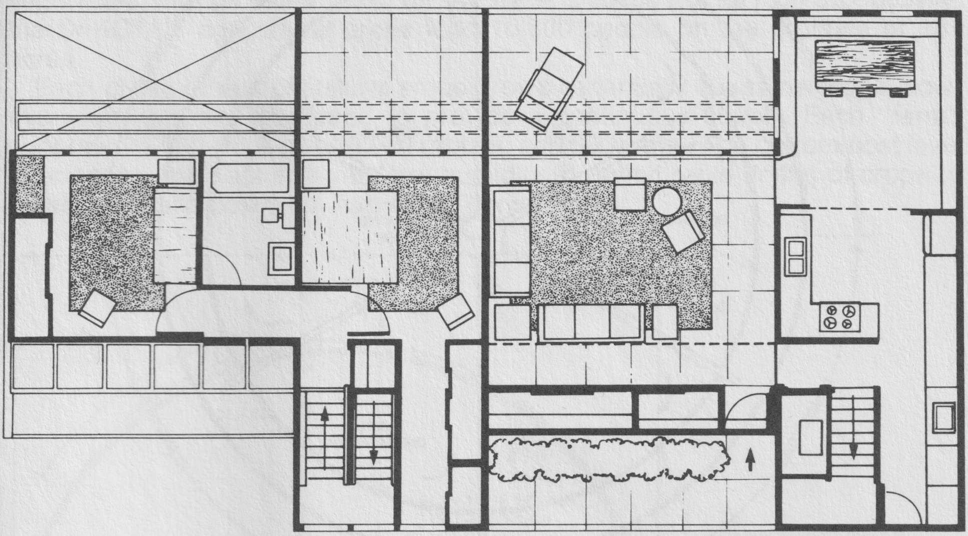


Figure 9: *Typical apartment plan*

Residences are the most numerous structures in this portion of the torus. A population of 10,000 is housed within 106 acres. The architecture maintains the feeling of open space by making full use of terracing structures up the curved walls. Much of the commerce (large shops, light industry, mechanical subsystems) is housed in the volume of the torus which lies below the central plain.

Housing in the DAKOTA is modular, permitting a variety of spaces and forms - clusters of one- or two-level homes, groups of structures as high as four and five stories, and terraced homes along the edges of the plain. The typical residence has ample window area to continue the sense of openness. Walls and doors are required only for acoustical and visual privacy; they are unnecessary as protection from the weather.

Agricultural Area

To promote diversity and duplication for safety's sake the torus is divided into three residential areas separated by three agricultural areas. The latter is segmented into controlled zones which may be completely closed off from other zones. This arrangement permits farmers to use higher than normal temperatures, carbon dioxide levels, humidity, and illumination in the controlled zones to force rapid growth. Partitioning also inhibits the spread of any disease of plants or animals from one zone to another.

Crops are grown in lunar soil about 0.3 m deep. This soil is made into a lightweight growth matrix of foamed, melted rock. Crop yields are greater than those achieved on Earth because of improved growing conditions and year-round farming. The higher levels of carbon dioxide, improved lighting, and temperature and humidity control increase productivity to approximately 10 times that of a typical American farm.

Each agricultural area is made up of tiers of fields and ponds, and cascading water. These multiple tiers triple cropland area. The upper level is surrounded by a number of ponds holding about 90,000 fish. There are similar ponds in each of the other two farming areas. The water flows from these ponds down to lower levels where it irrigates fields of corn, sorghum, soy beans, rice, alfalfa, and

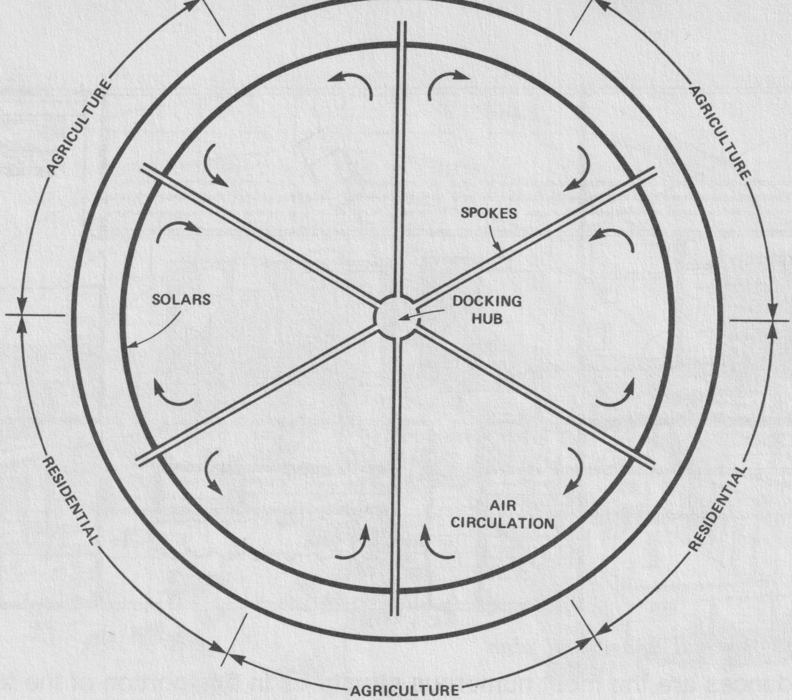


Figure 10: *Section showing distribution of residential and agricultural areas*

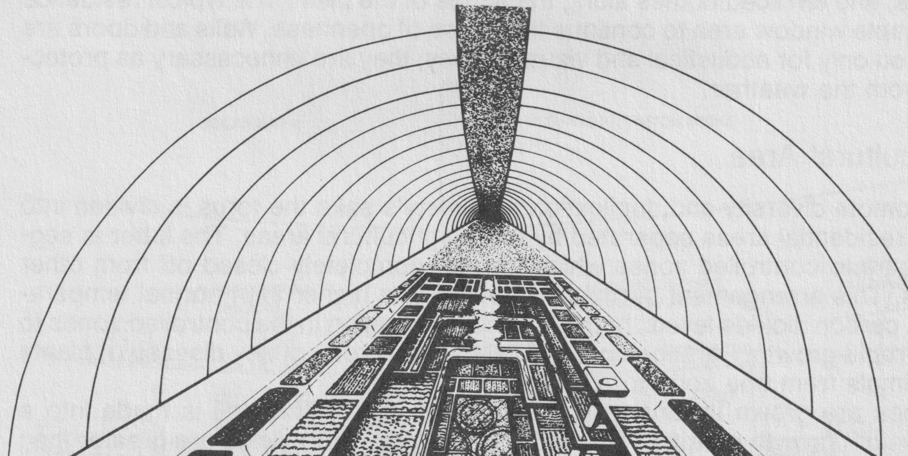


Figure 11: *View of agricultural area*

vegetables, and provides water for livestock. Because of its high productivity, the DAKOTA's agricultural areas feed 10,000 people on the produce of 151 acres.

Each of the three agricultural areas grows essentially the same crops; however, harvests are staggered to provide a continuous supply. Each "farm" supports 20,000 chickens, 10,000 rabbits, and 500 cattle. The bottommost level is enclosed and kept at a very low humidity to permit rapid drying of crops to hasten produce flow from harvest to consumption.

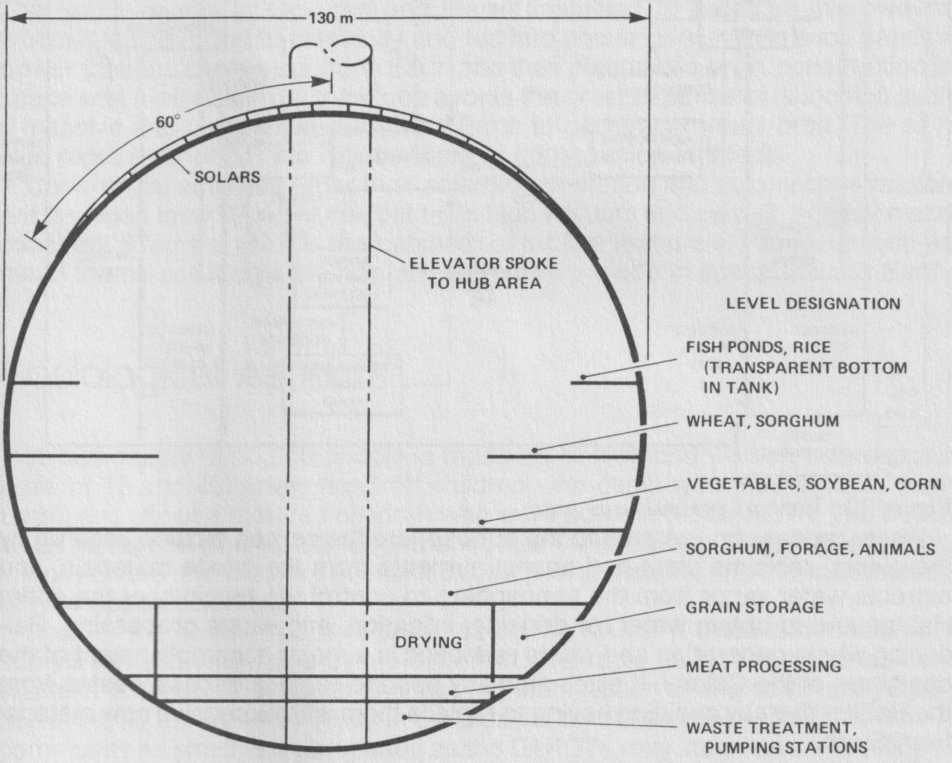


Figure 12: *Cross section of agricultural area*

Waste Processing Area

This vital part of the DAKOTA's life support system is located beneath the agricultural area. It maintains the balance between the two opposite processes of agricultural production and waste reduction.

On Earth production and waste reduction are balanced in part by natural processes. Water is extracted from the atmosphere by precipitation as rain; biodegradable materials are reduced by bacterial action. In space neither of these processes is fast or reliable enough. The DAKOTA, lacking oceans and an extensive atmosphere in which to hold wastes, is limited in its capacity for biomass and cannot duplicate Earth's natural recycling processes. Instead, it uses mechanical condensation of atmospheric moisture and chemical oxidation of wastes to reduce the recycling time to 1 1/2 hours. This approach minimizes the extra inventory of plants and animals necessary to sustain life and to provide a buffer against breakdowns in the system.

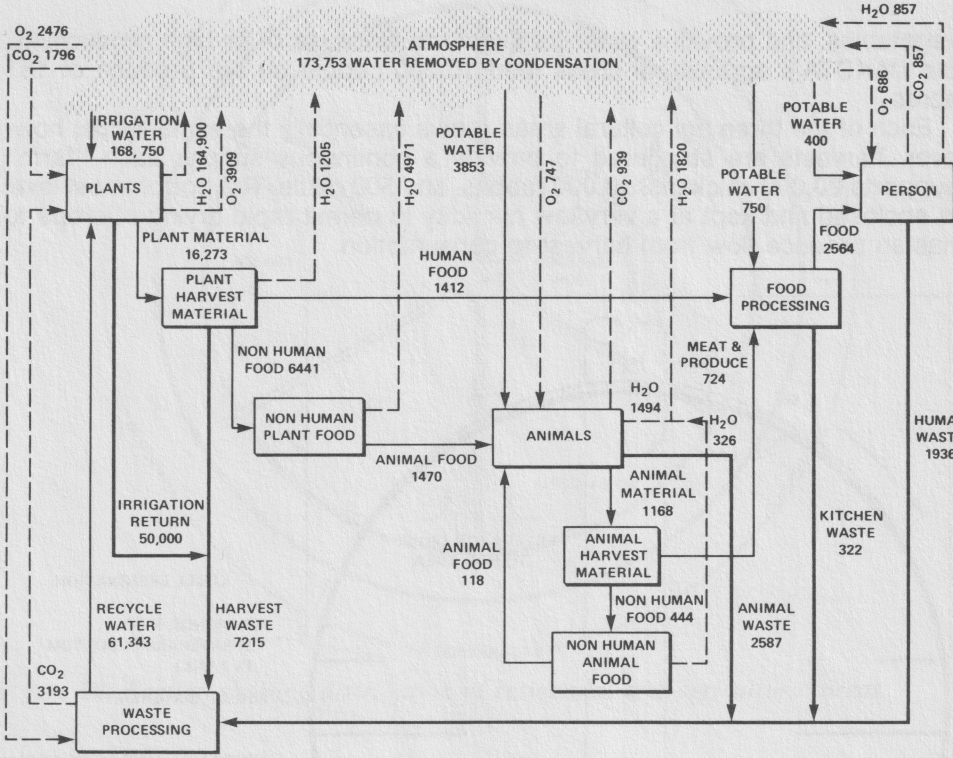


Figure 13: *View of agricultural area*

Waste processing restores to the atmosphere the carbon dioxide used up by the plants, reclaims plant and animal nutrients from the waste materials, and extracts water vapor from the atmosphere to control the humidity of the entire Habitat and to obtain water for drinking, irrigation, and waste processing. Balancing waste generation and waste reduction is a major accomplishment of the designers of the Colony. It eliminates any need to remove excess wastes from the Habitat thereby avoiding having to replace them with expensive new material from Earth.

Water is processed at two points in the system. Potable water for humans and animals is obtained by condensation from the air. Because evapotranspiration from plants accounts for 95 percent of the atmospheric moisture, most dehumidifiers are located in the agricultural areas. Plants rapidly replace the extracted water so the dehumidification system must be reliable. Otherwise the air would quickly saturate, leading to condensation on cool surfaces, the growth of molds and fungi, and an extremely uncomfortable environment. Several subunits are used for dehumidification.

Industry

The extraction facility is outside the DAKOTA, south of the hub some 10 km away. This location avoids the pollution of heavy industry and isolates a possible source of industrial accident from the Habitat. Although the plant is operated remotely so that it can be exposed to the vacuum of space, there are a number of small spheres attached to the plant where maintenance can be performed in a "shirt sleeve" environment.

The extraction facility has its own solar furnaces and a 200 mw electric power station run by solar energy. Bulk products such as aluminum ingots, oxygen gas, plate glass, expanded soil, and shielding material, are brought to the fabrication sphere by small tugs. However, small items and personnel make the trip from the hub through a pressurized transport tube.

In addition to constructing new space colonies, the DAKOTA manufactures satellite solar power stations. These power stations are the chief commercial reason for the Colony's existence. Placed in geosynchronous orbit, these solar power stations satisfy Earth's rapidly increasing demand for electrical energy. The Sun's energy is captured and then transmitted to Earth as microwaves where it is converted to electricity and fed into power grids. While such satellite power stations could be built on Earth and then placed into orbit, construction in space with materials from the Moon avoids the great expense of launching such a massive and complex system from Earth to geosynchronous orbit. The savings more than offset the higher costs of construction in space.

Commercial activities other than solar power station and colony construction are engaged in by DAKOTA residents. In high vacuum and zero-G, adhesion and cohesion effects dominate the behavior of molten materials. Products such as metal foams and single crystals are more easily made in space than on Earth.

Sociological Aspects

This community of 10,000 people is made up of men and women between the ages of 18 and 40, a few hundred children who came with their parents from Earth, and about a hundred children who were born on the DAKOTA. The population mix is that of a typical terrestrial frontier - it is hardworking, concentrating intently on the manufacture of satellite solar power stations and the construction of new space colonies.

Despite the narrow focus of activities on the DAKOTA there is considerable stimulation and innovation by the colonists. The rapid growth of the settlement sustains a sense of dynamic change; but stabilization of the community upon achieving its full size may result in the dissipation of this sense of excitement. A community as small and as isolated as the DAKOTA may stagnate and decline in productivity and attractiveness.

The answer to the problem is continued growth by the addition of more colonies. Growth is important economically as well as psychologically. As time passes, the population will become more like that of Earth in its age distribution, with the productive fraction of the population diminishing from about 70 percent to between 30 percent and 40 percent. Only if the total number of people grows rapidly can production in space be maintained at its initial level and be increased sufficiently to meet the growing demands of Earth's markets for satellite solar power stations. Furthermore, the aggregation of habitats into larger communities will enable the colonies to develop cultural and technological diversity similar to that which permits the larger cities of Earth to be centers of innovation and disseminators of cultural and technological change.

The DAKOTA enjoys the egalitarianism of a frontier reinforced by the spirit of a group of people working together with a sense of mission on a common task. This spirit, more than heroic adventures or romanticized challenge, is what makes the Habitat a rewarding place to live. Egalitarianism is tempered by certain realities within the DAKOTA. The entire Colony has a sense of elitism

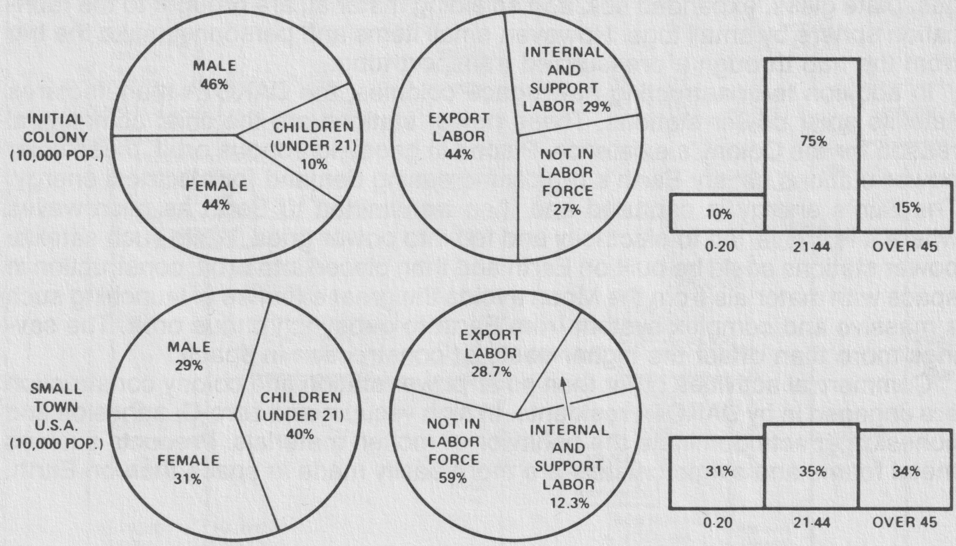


Figure 14: *Population distributions of sex, age, and productive effort in the DAKOTA and in a similar sized community on Earth*

simply because each individual colonist was selected as a settler. A distinction developing between those with clean or "shirtsleeve" jobs and those who work in hazardous, heavy industry, or zero atmosphere jobs, has only small effects and will not produce marked socioeconomic differentiation for a number of years.

TRANSPORTATION SYSTEM

The Space Colonization Project is supported by a sophisticated system of transport vehicles, each type designed for a specific purpose.

The Heavy Lift Launch Vehicle (HLLV), derived from 20th Century space shuttle designs, has either two or four solid boosters and automated avionics. It can accommodate a maximum of 200 passengers or 900 t of cargo. This transport is used to carry personnel and cargo from Earth to Low Earth Orbit (LEO).

When the HLLV achieves an LEO of 240 km above the Earth an entire section of the vehicle, the personnel carrier, is transferred to an Inter-Orbital Transport Vehicle (IOTV). This transporter moves people and cargo between points in space, and never lands on any planetary body. The IOTV's primary purpose is the ferrying of personnel and supplies from the staging area in LEO to the DAKOTA and Space Manufacturing Facilities (SMF) in Low Lunar Orbit (LLO). IOTVs also deliver cargo to Lunar Landing Vehicles (LLV) that carry supplies from LLO to the Tranquility Base Mining Facility. The trip from Earth to the DAKOTA takes about 5 days; from the DAKOTA to Tranquility Base about 2 weeks.

LEO serves as a vital point in the construction and supply of the DAKOTA. There, a space station consisting of crew quarters, a construction dock, and a supply depot has been assembled from materials made on Earth. The LEO Space Station, like many smaller structures in the Space Colonization Project, uses the Space Shuttle liquid hydrogen tank as the basic structural frame and pressure vessel. This design approach permits a high degree of commonality throughout much the Habitat system. It also provides a reasonable compromise between the safety features of small modular habitats used in early growth stages of a colony and the economies of scale of large monolithic structures. Extensive structural ribbing along the tank walls provides easy attachment of internal partitions and structures, permitting simple installation of the habitat interiors.

Pilot plants for materials extraction and fabrication, techniques for materials assembly, solar and nuclear power generation systems, are all tested in LEO which provides a vacuum and zero-G environment with relatively rapid access to Earth. Research on physiological effects of rotation and reduced gravity is conducted there also.

For the LEO station and the SMF habitat, several residential tanks are clustered around a communal tank. Each tank is divided into levels; the lowest level used for storage and maintenance equipment. In the residential tanks, seven of the levels are divided into three segments surrounding an elevator shaft to provide three studio apartments per level. Each apartment has 17.5 sq m (188.5 sq ft) of floor space, sufficient for one or two persons. One level (in the middle of

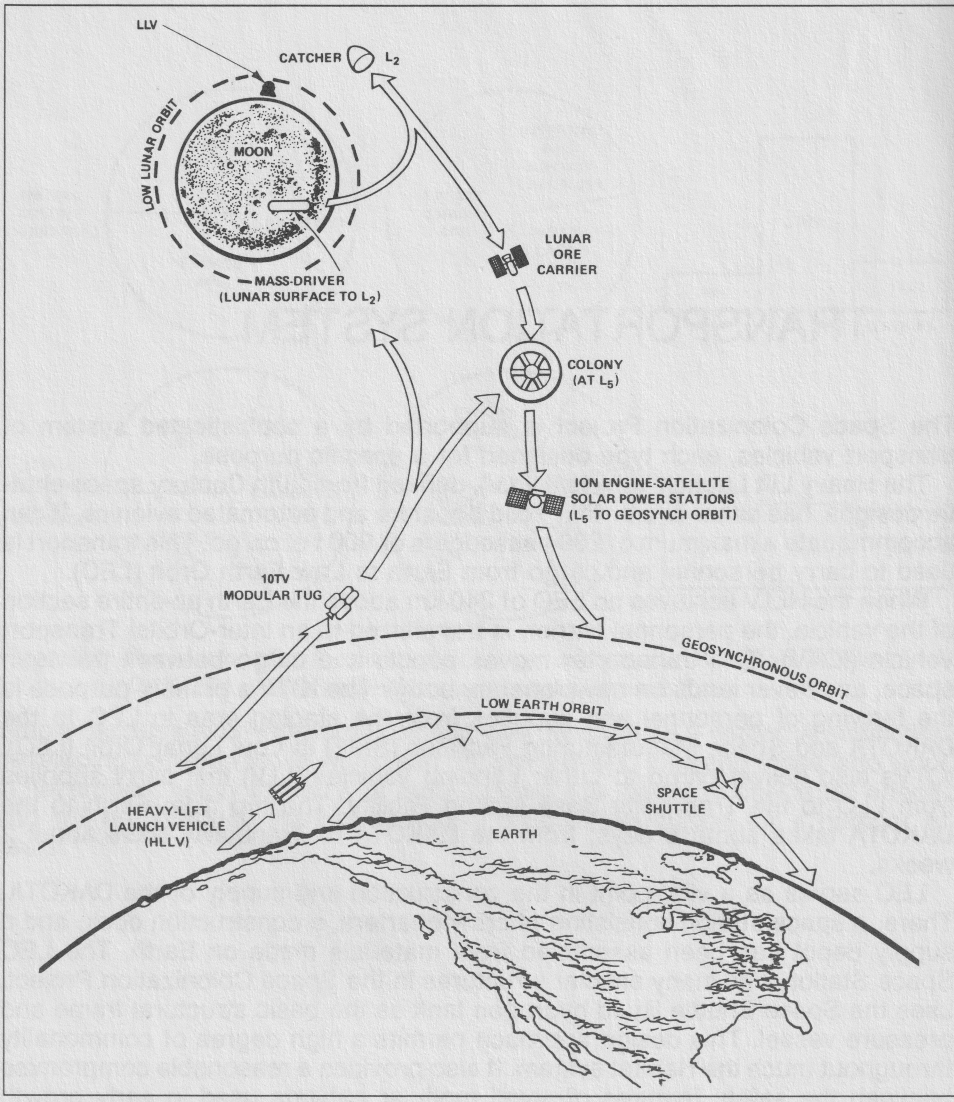


Figure 15: *Baseline transportation system*

the tank) provides toilet, bath, and laundry facilities, while the top level (in the upper hemispherical dome) is used as a leisure and social area (game room, observation deck).

Each tank has an emergency airlock at the top level, with routine entry into the habitat through two airlocks in the hub. One of the dining room levels (of the six provided in the two communal tanks) is used as a medical clinic/emergency operating room.

The SMF includes equipment to extract oxygen from unselected lunar soil by reduction with hydrogen. The resulting water vapor is collected in a cold trap. The hydrogen is recovered by electrolysis, and the oxygen is used either for life support or liquified for use in the IOTV and the LLV. The extraction of aluminum from anorthosite is also done at the SMF. Most of the factory mass is taken up by chemical processing equipment and fabrication machinery for the production of structural sheets, plate, beams, and glass.

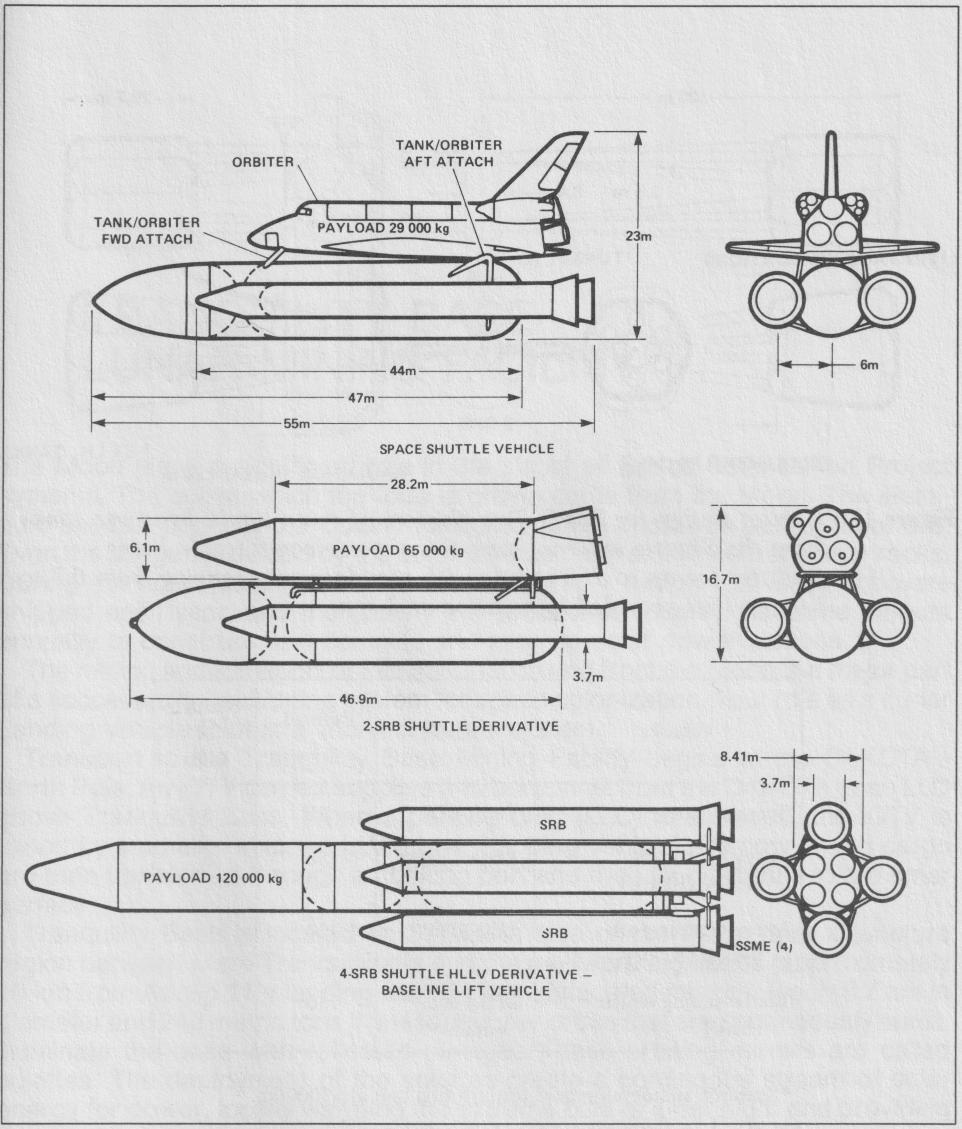


Figure 16: *Shuttle derivatives for transport of people and goods from Earth to Low Earth Orbit (LEO)*

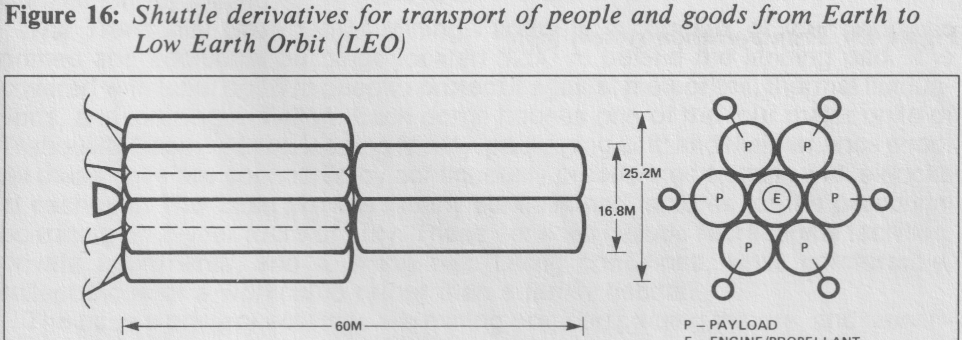


Figure 17: *SSME powered modular tug*

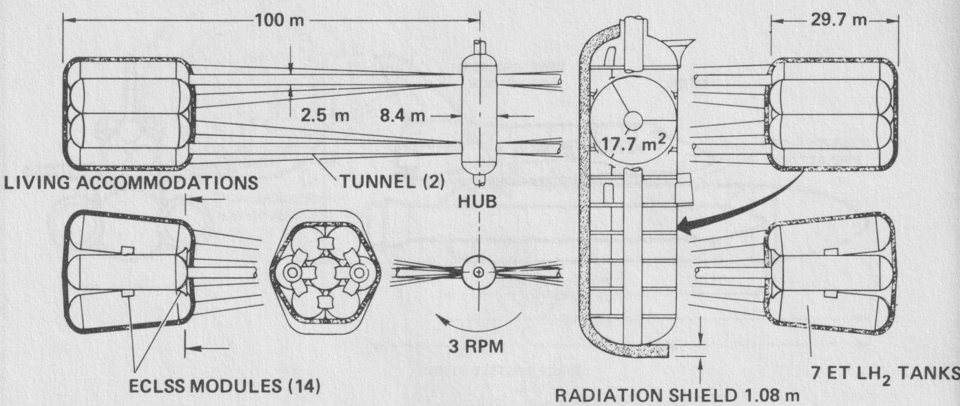


Figure 18: *Habitat design for SMF. Two clusters of seven liquid hydrogen tanks from the Shuttle external tank sets provide comfortable living facilities for up to 252 people with pseudogravity ranging from 0.7 to 1.0 gravities provided by rotation at 3 rpm*

Vehicles	Route	Payload, t	Number of units
Space shuttle	Earth-LEO**	30	3
Heavy lift launch vehicle (HLLV)	Earth-LEO**	150	6
Interorbit transport vehicle (IOTV)	LEO-LPO**	300	9
Lunar landing vehicle (LLV)	LPO-Lunar surface**	150	4

*Research and development through first unit at $5000/kg.

**LEO: Low Earth orbit; LPO: Lunar parking orbit.

Figure 19: *Transportation system table*

TRANQUILITY BASE LUNAR MINING FACILITY

The Moon plays a significant role in the life of all Space Colonization Project systems. The soil in which the food is grown came from the Moon. The aluminum used throughout the Colony for construction once was part of lunar ore. Even the oxygen breathed by the colonists has been extracted from lunar rocks. During the construction phase of the DAKOTA, 1 million t of lunar ore were shipped each year, and the Colony still processes roughly the same amount annually to construct new colonies and satellite solar power stations.

The mining and transport of this material on and from the Moon is a major part of a successfully functioning system for space colonization. Your role as a Lunar Landing Vehicle Pilot is a vital link in this system.

Transport to the Tranquility Base Mining Facility begins at the DAKOTA's North Pole. An IOTV carries supplies and personnel from the DAKOTA to an LLO above Tranquility Base. When a parking orbit (LLO) is achieved, the IOTV is joined by a smaller ship, an LLV (Lunar Landing Vehicle). Personnel and cargo are then transferred through a docking port and the LLV descends to the lunar surface.

Tranquility Base is located on the Earth side of the Moon near a juncture region between Mare Tranquillitatis and the eastward highlands (approximately 20 km from Apollo 11's landing site). Four multifaceted mirrors (each 8.7 km in diameter and 240 metric tons in mass) in lunar orbits that are continuously sunlit, illuminate the base with reflected sunlight. These orbiting mirrors are called solettas. The deployment of the solettas create a continuous stream of solar energy for power, locally warming the extreme cold of lunar night and providing illumination for mining.

The Tranquility Base Lunar Mining Facility is a complex of four geodesic domes and additional buildings located 3200 m behind the landing pad. It is covered with lunar soil 5 m deep to protect it against meteorites, thermal fluctuations, and ionizing radiation. Each dome houses one of the four major units of Tranquility Base: habitat; loading facility; packaging unit; and maintenance shop. All these units are connected by continuously pressurized tunnels with airlocks at each end. The Base provides many services and facilities for the personnel operating on 2-year tours of duty. These services include recreational facilities, private apartments, and a dining hall. Living conditions, while comfortable, reflect those of a workcamp rather than a family habitat.

The base's primary activities are mining ore, compacting the ore, and launching it to the mass catcher at L_2. The base also supports exploration and research efforts. During mining operations, there are only 150 persons at the base of

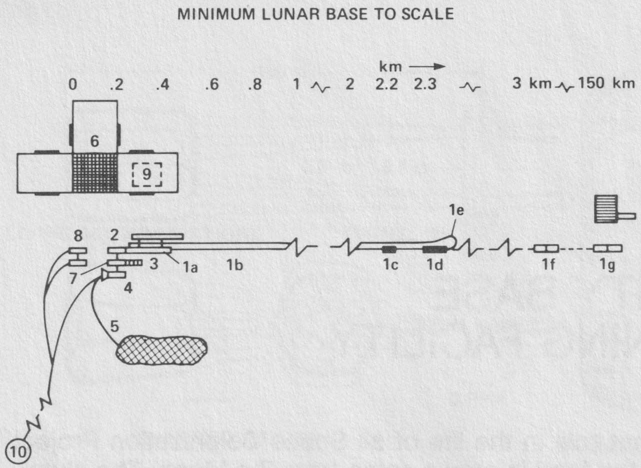


Figure 20: *Schematic scale view of Tranquility Base Lunar Mining Facility with main features identified*

1. MASS DRIVER
   - 1a. ACCELERATOR SECTION
   - 1b. DRIFT AND STABILIZATION SECTION
   - 1c. PAYLOAD RELEASE AND BUCKET DEFLECTION SECTION
   - 1d. BUCKET DECELERATION SECTION
   - 1e. RETURN TRACK LOOP
   - 1f. INITIAL TRIM STATION, SOLAR ARRAY AND MINI-HABITAT
   - 1g. FINAL TRIM STATION
2. LOADING FACILITY
3. STOCKPILE BEN
4. PACKAGING UNIT
5. TRUCKS AND HAUL-ROAD TO PIT
6. SOLAR POWER ARRAY AND SIDE MIRRORS
7. MAINTENANCE FACILITY
8. HABITAT
9. CRYOGENICS STORAGE VOLUME UNDER ONE SIDE MIRROR
10. LANDING PAD AND ACCESS ROAD

whom approximately 40 are support personnel. Almost all activities are in a "shirt sleeve" environment within the shielded structures. A large area is provided for repair work.

Mining and Processing

Ore is excavated from the lunar surface by digging holes approximately 2 km across and 10 m deep at several sites. In order to supply 1 million metric tons of lunar ore per year to the DAKOTA, a surface area the size of about 8 football fields must be mined annually. The mining machinery operates 50 percent of the time, requiring a mining rate of about 4 t/min (about 1 m³/min).

Soil is scooped and carried to the processor by two scooper-loaders. Ore is carried from the mining area on a conveyor system. At the launch area it is compacted to fit into a launcher bucket, and then fused.

The continued viability of the DAKOTA depends on transporting large quantities of lunar material from the Moon to the DAKOTA without large expenditures of propellant. The ore delivery system is divided into three parts: launching the material from the Moon, collecting it in space, and moving it to the Colony.

The Mass Launcher

The mass launcher delivers pellets of lunar ore from the Moon into space. This electromagnetic mass accelerator launches small payloads in a special bucket containing super conducting coil magnets. Buckets containing 10 kg of compacted lunar material are magnetically levitated and accelerated at 30 g by a linear, synchronous electric motor.

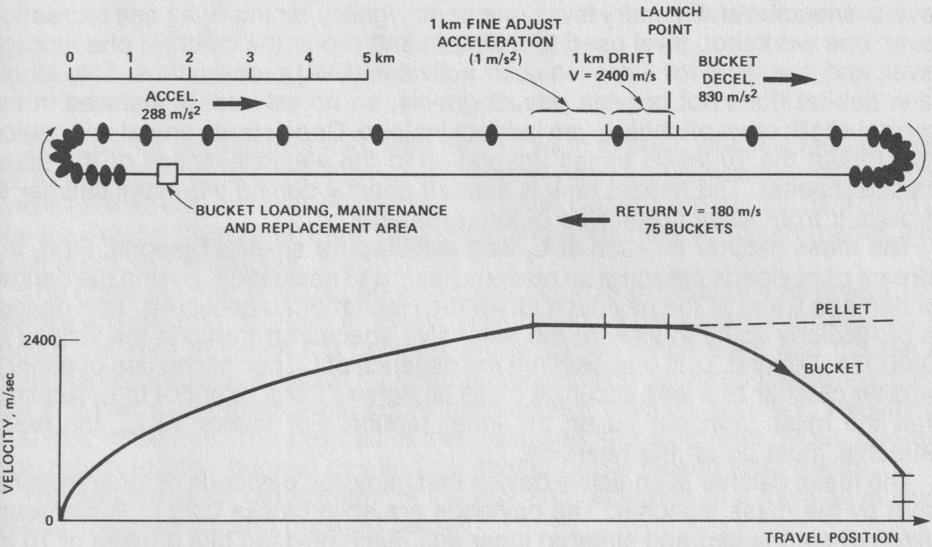


Figure 21: *The mass launcher*

Each second the mass launcher accelerates five 10 kg masses of lunar material to lunar escape velocity of 2400 m/s. During acceleration the payload is tightly held in the bucket, but when lunar escape velocity is reached the payload is released. Since the bucket is constrained by a track to follow the curve of the lunar surface, the payload rises relative to the surface and proceeds into space.

The launch sequence for a payload of lunar material is:

Coarse acceleration—10 km at 288 m/s². Velocity is measured along the track in real time using a laser doppler

Fine acceleration—1 km at 1 m/s²

Drift—1 km with deceleration due to electromagnetic drag. A tradeoff exists between errors in launch velocity and errors in launch location; the launch is the event of payload release. This release occurs at a location calculated on the basis of the tradeoff, using the measured velocity

Deceleration of the bucket and return to loading zone

Downrange adjustment of the ejection velocity (i.e., velocity trimming) of the lunar soil packets is accomplished by means of two trim stations. Each packet is electrostatically charged as it enters the trim station. In the trim station, electric fields parallel and perpendicular to the packet's velocity vector precisely adjust the packet's trajectory and velocity. The two trim stations are located 3 and 150 km downrange. Small blast deflectors are built into the fronts of correction tube trenches so that debris from ruptured or off-course packets will pass over the recessed correction tubes.

The Mass Catcher

The problem of collecting the stream of material launched by the mass launcher is solved by a kind of automated "catcher's mitt," the mass catcher, located at L_2. Although the catcher is fully automated there is a 12-person space station at L_2 for maintenance personnel.

This space station consists of one tank that is divided into four residential levels: one toilet and laundry level; one pantry/galley/dining level; one recreation level; one workshop level used to maintain and repair the catcher; one storage level; and one level for extravehicular activities (EVA) preparations. This single tank habitat does not provide pseudogravity, so no elevator is installed in the central shaft; crew members use ladders instead. Consistent vertical orientation throughout the 10 levels eases adaptation to the weightlessness of the mass catcher habitat. The habitat tank is located directly behind the mass catcher to protect it from stray projectiles of lunar material.

The mass catcher location at L_2 was selected for several reasons. First, the stream of payloads presents an obvious hazard to navigation, posing the danger of damage if any of the payloads strike the Habitat or a spacecraft. This danger is particularly acute in view of the extensive spacecraft traffic in the vicinity of DAKOTA. Second, L_2 is one-seventh the distance of L_5, permitting use of either a smaller catcher or a less accurate mass launcher. Third, to shoot to L_5 requires that the mass launcher be on the lunar farside. For launch to L_2, the mass launcher must be on the nearside.

The mass catcher is an active device that captures payloads of lunar material shot by the mass launcher. The payloads are solid blocks 0.20 m in diameter, made of compacted and sintered lunar soil. Each payload has a mass of 10 kg and arrives at L_2 with a speed of 200 m/s.

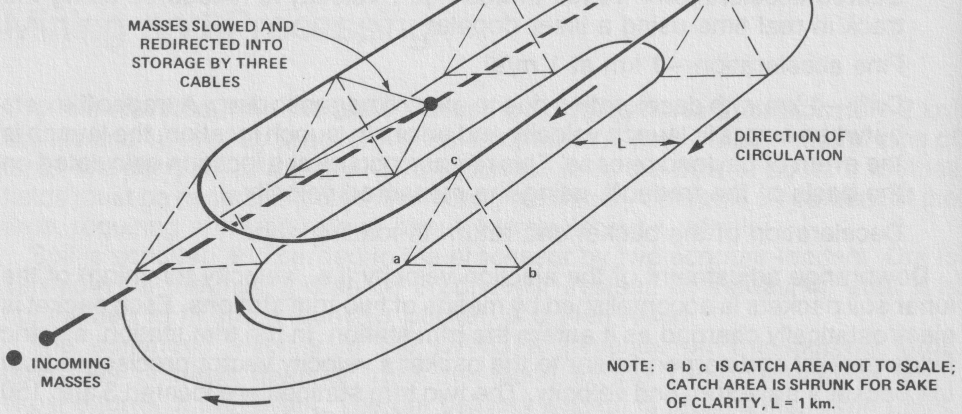


Figure 22: *The mass catcher*

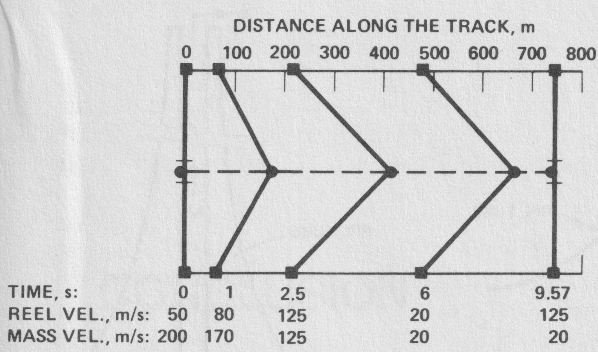


Figure 23: *Two-dimensional representation of the sequence of events in the mass catcher*

The catcher is actually a thin, light net, 10 sq m in area, which is manipulated by three cables to position the net anywhere within an equilateral triangle. The cables are wound on reels which move on three closed loop tracks. Each side of the equilateral triangle is 1 km, thus providing a 430,000 sq m catch area. The total mass of the catcher is 220 t.

The mass catcher is equipped with radar capable of detecting payloads 10 s before arrival, that is, 2000 m away. A signal from the radar is processed to locate the spot at which the payload will cross the catch area, and the net is manipulated into that position for interception. Having captured the payload, the net and reel assemblies (rigs) act to decelerate it from its incoming velocity of 200 m/s to 20 m/s. The payload is then released into a storage depot, and the rigs return to their original position by means of the closed loop tracks.

The sequence for deployment of the rigs and reception of a payload is illustrated in Figure 23 and outlined below:

> The payload enters the catcher area with a velocity 200 m/s where it is decelerated constantly by 30 m/s^2. When its velocity reaches 20 m/s, it is released to a storage depot attached to the rear end of the catcher frame.

The mass catcher uses an unusual propulsion device—a rotary pellet launcher (RPL)—to position the catcher so that it is always facing the incoming

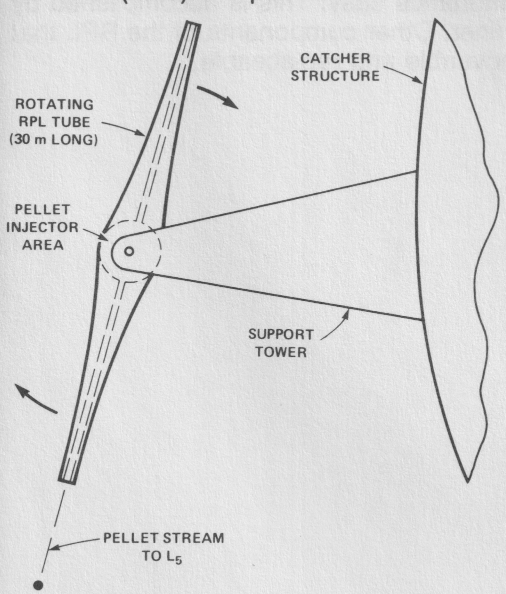


Figure 24: *The rotary pellet launcher*

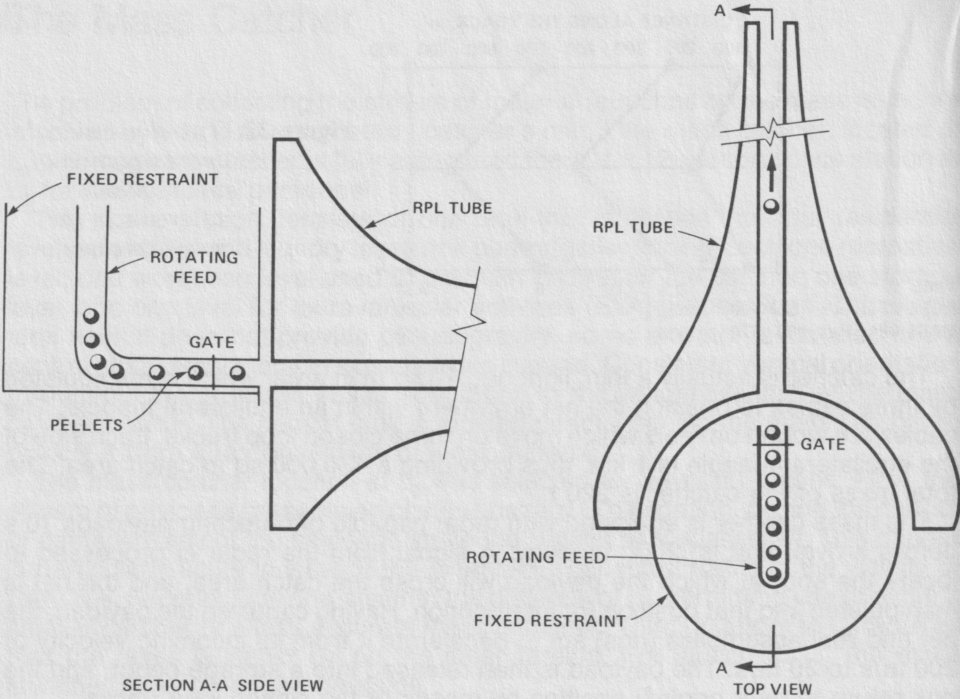


Figure 25: *RPL injector schematic*

stream of payloads. The RPL is a heavy tube rapidly rotating so as to accelerate small pellets of rock. The tube consists of a straight, nontapered section near the end and an exponentially tapering section inward toward the hub from the nontapered section.

The RPL is subject to considerable wear due to friction and abrasion from the pellets, and is designed to make maintenance easy. This is accomplished by providing the tube with a removeable liner. Other components of the RPL that are subject to high wear also are removeable and replaceable.

CONCLUSION

Earth is a planet of delicate ecological balance, finite resources, and ever-escalating human population. Space offers new possibilities, new resources, new frontiers, and new challenges.

Space also offers riches: great resources of matter and energy. Solar energy, collected in space, converted to electricity, and beamed to Earth is of enormous value. The manufacture of satellite power stations to bring this energy to Earth and other commercial activities that use solar energy, and the high-vacuum weightless environment of space are highly successful economic ventures.

You are a part of the great adventure of space colonization. Every part of the system—the DAKOTA Space Habitat, the Tranquility Base Lunar Mining Facility, and the 10,000 colonists, technicians, and pilots—is vital to its ultimate success.

What has been described here is merely the beginning of a vast complex of space colonies. Eventually, man will live in colonies placed at the outposts of our universe. From this vantage point, he can unchain the Earth from its present limitations and unlock the secrets of the stars.

PILOT TRAINING MANUAL

Lunar Landing Vehicle Description
Pre-flight Instructions
Exercise 1: SOFT LANDING
Exercise 2: HOVERING
Exercise 3: MANEUVERING DURING HOVER
Exercise 4: LANDING FROM APPROACH
Exercise 5: BASE LANDING FROM APPROACH
Exercise 6: DESCENT TO BASE FROM ORBIT
Exercise 7: LIFTOFF
Exercise 8: FLIGHT TO EMERGENCY LANDING PAD
CARGO RUN MISSION
SOLO FLIGHT EXCURSIONS

LUNAR LANDING VEHICLE (LLV)

Specifications

Length	20 meters
Diameter	15 meters
Cabin Mass	10,000 kilograms
Engine Section Mass	25,000 kilograms
Propellant Mass	700,000 kilograms
Maximum Payload Mass	735,000 kilograms
Crew	2 (Pilot, Navigator)

Performance

Thrust	3,800,000 newtons
Maxium Acceleration (from surface, full payload)	3 meters/second^2
Maximum Altitude	6,500 kilometers
Maximum Landing Velocity	3 meters/second
Typical Voyage Duration (LLO to surface or return)	55 minutes

Subsystems Overview

Engines	1 Main Propulsion; 4 Attitude Quads
Fuel	Liquid Oxygen and Liquid Hydrogen at 6:1 mix ratio
Electrical Power	Hydrogen/Oxygen Fuel Cells
Navigation	Optical Tracker-Controlled Inertial Guidance
Atmosphere	21% O_2; 11% humidity

The Lunar Landing Vehicle (LLV) is the workhorse of the Tranquility Base Mining Facility. Your training simulator models most aspects of this ship. The LLV is used primarily for ferrying passengers and payload from the Inter-Orbital Transfer Vehicle (IOTV) in Low Lunar Orbit (LLO) to Tranquility Base. A spidery-looking vehicle, the LLV has a spherical cabin, an octagonal propulsion section, and four legs set on the othogonal axes of the lander (forward, aft, left, and right).

The cabin houses the crew and any passengers or payload. Its exterior has recesses for radar and communications equipment, and a large cockpit window of extremely strong glass. This window affords the crew an excellent forward field of view. The line of sight is perpendicular (at a 90 degree angle) to the ship's vertical axis so that when the LLV is resting on the ground, the window looks forward. (In your simulator, the computer screen represents the cockpit window).

There are no seats in the cabin; the LLV is subject to very moderate G forces and human legs are good shock absorbers. Standing allows the crew to get close to the instruments and improves their ability to see downward toward the Moon's surface. Harnesses and other restraint systems tether passengers and crew during weightless flight and prevent them from being jostled during landing. The cabin has two universal docking hatches with airlocks, one at the top center of the cabin and one aft.

The engine section is located directly below the cabin. It houses the main engine, fuel supply, and various storage tanks. Attached to the engine section is the landing gear which uses hydraulic shock absorbers to handle a diversity of impact loads. It is also designed to accommodate a variety of landing conditions such as protruberances, depressions, small craters, and slopes.

The spacecraft's subsystems are its heart. Subsystems are mechanical or electronic devices that perform specific functions such as providing oxygen to the crew or navigating the craft. Your LLV simulator models subsystems for propulsion, attitude control, and navigation.

The propulsion subsystem is made up of engines, propellant tanks, valves, and plumbing. A single ascent/descent engine points downward from the engine section to provide translational motion. When the LLV is resting on the lunar surface, the engine points straight down towards the ground. When the LLV is pitched at −90 degrees, the engine points toward the horizon and the window points down; when pitched at +90 degrees, the engine points toward the horizon and the window points up. Your LLV has a nongimbaled (non-swivelling) engine, so you can not change the direction in which the engine points without changing the spacecraft's attitude. The engine is pressure-fed from the main propulsion tanks and has a variable thrust of up to 3,800,000 newtons (about 760,000 pounds).

The LLV also has four attitude control "quads" (a four-engine package) to control its rotation. These are fixed-thrust engines that are fueled from an auxiliary propulsion tank, allowing the pilot to pitch and roll the spacecraft without drawing on the main fuel supply. The quads protrude from the cabin section, and are positioned so that the downward-thrusting attitude control engine fires between the two nearest landing legs.

The control subsystem directs the LLV's movement with relation to its velocity (speed and direction) or attitude (pitch and roll). The main ascent/descent engine has a variable control, allowing the pilot to throttle thrust from 10% to 100%. The LLV is an inertial vehicle: when the pilot applies thrust along a particular direction, the spacecraft continues to move in that direction until a modifying force is applied (by gravity or thrust in the opposite direction).

Quad controls, which allow attitude to be changed independent of the main engine setting, are much more sophisticated. A stability augmentation system cancels the effects of inertia when rotating the ship. This allows the pilot to precisely set and maintain the craft's pitch and roll angles with a single adjustment. (There are no controls for yaw in this simulator.) Dampers prevent the pilot from pitching and rolling the craft too far. The LLV can be pitched from -90 degrees to 90 degrees. When pitch is between 36 degrees and -36 degrees, the LLV's stability augmentation system allows the craft to be rolled from -10 degrees (to the left) to 10 degrees (to the right).

The most complex LLV subsystem is the guidance and navigation system. Guidance means directing the movement of a spacecraft to a selected path or trajectory. Navigation, in space as on the seas, refers to determining present position, as accurately as possible, with relation to a fixed reference point. This system consists of a microcomputer, radar, communications equipment, the inertial measurement unit (IMU), and a space sextant. Together, they determine the spacecraft's precise location, and how best to burn the engines to correct the ship's course with minimum fuel consumption. Note that in your LLV trainer, this system is simulated only to the extent of providing present position, velocity, and attitude relative to the Tranquility Base landing pad.

Position is measured in meters (m) or kilometers (km) along three axes: X, Y, and Z. The **XRNG** gauge on the control panel measures lateral motion along the X axis. Positions to the left of the landing pad are given as negative values; positions to the right are positive values. Horizontal motion along the Y axis is displayed as the **DIST** reading on the control panel. Positions forward of the landing pad are negative; positions behind the landing pad are positive. Finally, altitude, or vertical position, is shown as **ALT** (altimeter) reading. This reading always has a positive value.

Velocity also is measured along these same axes relative to the landing pad; the readouts on your control panel are **VELX** = X axis, **VELY** = Y axis, and **VELZ** = Z axis. Velocity is measured in meters per second (m/sec).

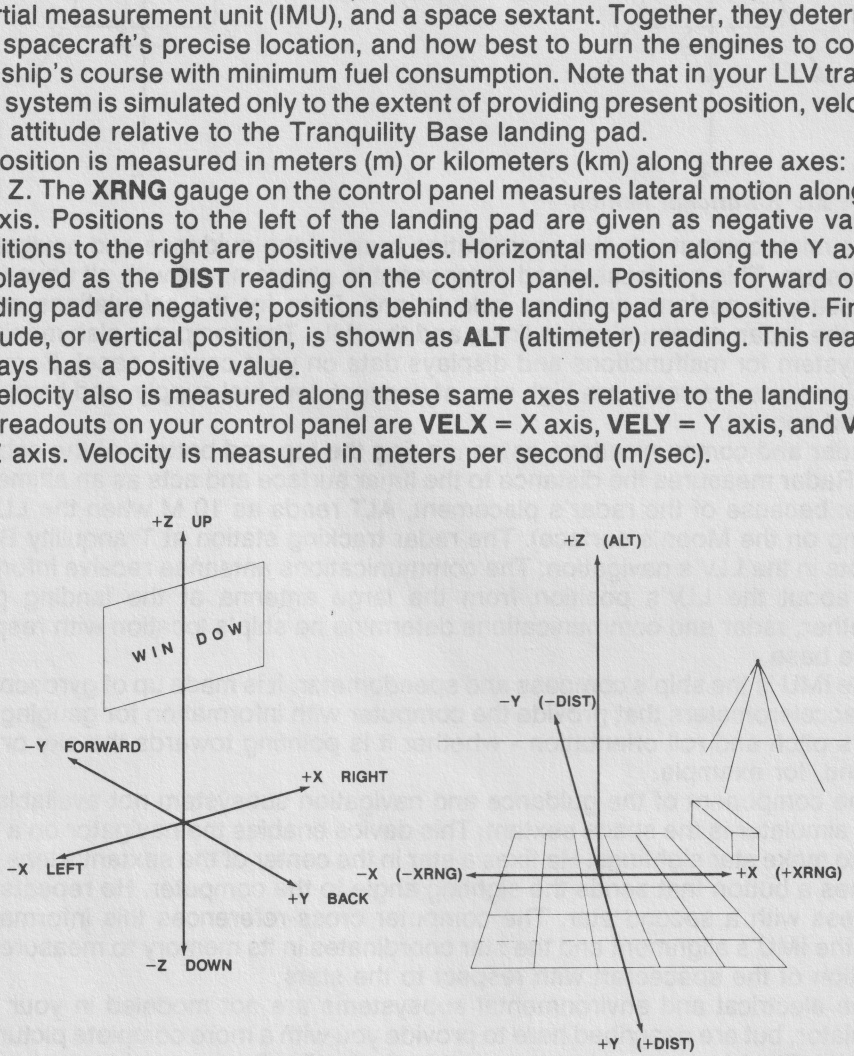


Figure 26: *Translational motion with respect to the LLV (a) and the landing pad (b)*

Attitude is measured in degrees. Pitch refers to rotation around the X axis. **PTCH** is negative when the spacecraft window faces the ground; it is positive when the window faces the sky. **ROLL** refers to rotation around the Y axis. A negative **ROLL** is a bank to the left; a positive **ROLL** is a bank to the right.

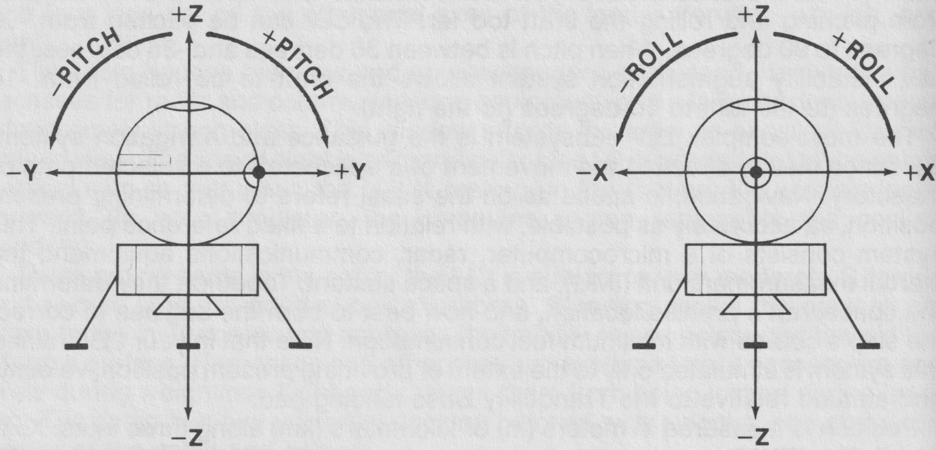


Figure 27: *Rotational motion*

The microcomputer is the coordinating brain of the guidance and navigation subsystem. This briefcase-sized component is programmed with all equations necessary to perform guidance calculations. Data for the calculations come from the radar, communication links, and the IMU. The computer also monitors the system for malfunctions and displays data on your control panel. Some of the situations it detects are high rate of descent, low fuel supply, and imminent ground contact.

Radar and communications antennae ring the top and bottom of the cabin's hull. Radar measures the distance to the lunar surface and acts as an altimeter. (Note: because of the radar's placement, **ALT** reads as 10 M when the LLV is resting on the Moon's surface). The radar tracking station at Tranquility Base assists in the LLV's navigation. The communications antennae receive information about the LLV's position from the large antenna at the landing pad. Together, radar and communications determine he ship's location with respect to the base.

The IMU is the ship's compass and speedometer. It is made up of gyroscopes and accelerometers that provide the computer with information for gauging the ship's pitch and roll orientation - whether it is pointing towards the sky or the ground, for example.

One component of the guidance and navigation subsystem not available on your simulator is the space sextant. This device enables the navigator on a real LLV to make star sightings. He fixes a star in the center of the sextant's lens and pushes a button that sends the sighting angle to the computer. He repeats the process with a second star. The computer cross-references this information with the IMU's alignment and the star coordinates in its memory to measure the position of the spacecraft with respect to the stars.

The electrical and environmental subsystems are not modeled in your LLV simulator, but are described here to provide you with a more complete picture of the LLV. Electrical power is generated by fuel cells. Oxygen and hydrogen are stored as liquids at extremely cold temperatures in leakproof, insulated containers. When combined chemically, they yield electric power and, as a byproduct,

water for drinking. The fuel-cell power system is efficient, clean, and pollution free.

The environmental control system provides life support for the crew and passengers. Cabin atmosphere is maintained at 14.7 psi (standard sea-level air pressure) at a mix of 79% nitrogen and 21% oxygen. The cabin pressurization system has two oxygen supplies, two nitrogen supplies, and an emergency oxygen system. Canisters filled with lithium hydroxide and activated charcoal remove carbon dioxide and odors from the cabin's air. The life support system also maintains the cabin temperature at a comfortable level, provides hot and cold water, and circulates coolant to keep the electronic gear at the proper temperature. Because lives depend on this system, most of the functions are provided in duplicate, in case of failure.

LLV SIMULATOR TRAINING EXERCISES

Welcome to the Tranquility Base Pilot Training Program. You have been selected as a candidate for the Lunar Landing Vehicle Pilot Corps. Your training will include classroom study, field excursions, and flight training on a simulator. You should master all eight maneuver categories before you begin hands-on training in a real LLV, a Cargo Run Mission, or solo flight.

Training in the LLV simulator is divided into eight exercise categories. Exercises will be taught in the order below. They are:

Exercise 1: SOFT LANDING - Introduction to LLV. Achieve an altitude of 6000 m above the lunar surface. Return to the Tranquility Base landing pad and execute a soft landing.

Exercise 2: HOVERING - Master techniques for stopping ascent or descent of LLV and for maintaining a constant altitude above the Moon's surface.

Exercise 3: MANUEVERING DURING HOVER - Master pitch and roll maneuvers to move LLV forward, back, and laterally during hover.

Exercise 4: LANDING FROM APPROACH - Assume control of LLV at a distance of between 10 km and 20 km from lunar base. Using only pitch and thrust controls, reduce speed and land on the Moon's surface. Achieving soft landing is more important than location of landing.

Exercise 5: LANDING AT BASE FROM APPROACH - Assume control of LLV on approach and land safely within 500 m of the center of the Base landing pad.

Exercise 6: DESCENT TO BASE FROM ORBIT - Assume control of LLV during orbit at an altitude greater than 50 km and land safely within the perimeter of the Base landing pad.

Exercise 7: LIFTOFF - Assume control of LLV while stationary at Tranquility Base landing pad, then take LLV into lunar orbit.

Exercise 8: FLIGHT TO EMERGENCY LANDING PAD - Lift-off from Tranquility Base landing pad. Navigate to emergency landing pad, execute a soft landing, refuel, and then return to Tranquility Base.

Pre-flight Instructions

(see Craft Control Summary card)

APPLE Insert the *Lunar Explorer* disk in your disk drive and turn on your computer and monitor. The title page and then the cockpit menu appear. Press **[K]** to use keyboard controls, or **[J]** to use joystick controls.

IBM Insert your DOS disk in Drive A and turn on your computer and monitor. Enter the date and time when the prompts appear. When you see **A>**, insert your *Lunar Explorer* disk in Drive A, type **EXPLORER**, and press **[ENTER]**.

It is not necessary to select keyboard or joystick. Control mode is automatically recognized by the program. If cockpit screen is off-center, use **[SPACEBAR]** to move the picture right and **[BACKSPACE]** to move the picture left until the cockpit is centered on your screen.

Press **[D]** to see the demonstration
Press **[G]** to begin flight training on the ground
Press **[A]** to begin approach exercises
Press **[O]** to begin orbit exercises
Press **[C]** to begin cargo run mission

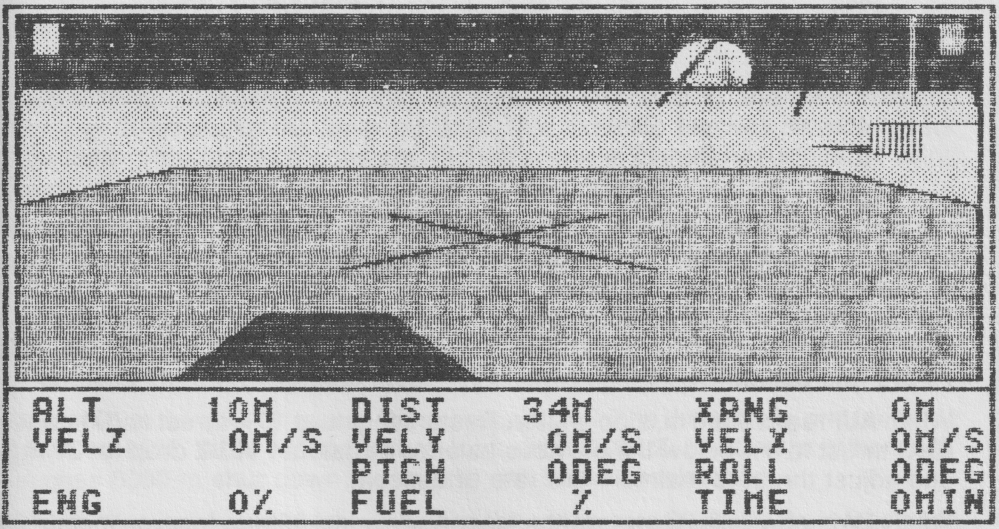
All flight exercises begin at these menu selections. To end a flight during an exercise and return to the cockpit menu, press **[ESC]**. You can "stop the action" at any time during a flight by pressing **[SPACEBAR]**. To resume the flight, press any LLV control key.

Exercise 1: SOFT LANDING

OBJECTIVE: Achieve an altitude of 6000 m above Tranquility Base and return to your launch point.

DESCRIPTION: This first exercise is relatively simple. You must control thrust as you ascend to an altitude of 6000 m, then descend and execute a safe landing. This exercise does not involve horizontal (forward/back along the Y axis) motion or lateral (left/right along the X axis) motion. This soft landing exercise concentrates on vertical (up/down along the Z axis) motion.

From the cockpit menu, press **[G]** and you see:



You are looking at the landing pad from the pilot's point of view. You are seated approximately 34 m from the pad's center. Refuel your LLV.

APPLE Set coarse thrust adjustment:
press **[0]** to increase or decrease thrust in 10% increments
press **[2]** to increase or decrease thrust in 2% increments

IBM 1% increment is automatic. No setting is needed

Start your engine. **ENG** on your control panel should show a thrust of 10%. Increase thrust to 60%. Now you should be observing lift-off through your cockpit window. **VELZ** and **ALT** are increasing as you gain speed and altitude.

Reduce thrust by small increments until **VELZ** stops increasing. Your craft should be climbing at a constant **VELZ**. The thrust percentage that maintains a constant **VELZ**, **VELY**, or **VELX** is called the balance thrust. To increase **VELZ**, increase thrust. To decrease **VELZ**, decrease thrust.

As your craft consumes fuel, it becomes lighter and therefore requires less thrust to maintain a constant climbing rate (or constant VELZ).

Maintain **VELZ** at 20 m/s. If **VELZ** is less than 20 m/s, increase thrust to slightly above the balance thrust until **VELZ** reaches 20 m/s. When a 20 m/s **VELZ** is achieved, return to balance thrust. If **VELZ** is more than 20 m/s, reduce thrust

slightly. Use fine thrust adjustments to thrust and maintain **VELZ** at 20 m/s. The balance thrust, at a pitch angle of 0 deg and a typical approach speed, approximates the following:

FUEL	BALANCE THRUST
99%	48%
93%	46%
87%	44%
81%	42%
74%	40%
68%	38%
62%	36%
56%	34%
49%	32%
43%	30%
37%	28%
31%	26%
24%	24%
18%	22%
12%	20%
6%	18%

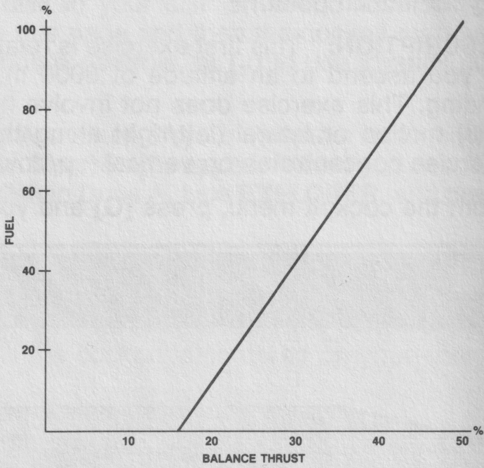


Figure 28: *Graph of Balance Thrust versus Fuel*

These figures are estimates and are not to be used as exact calculations. The relationship between Fuel and Balance Thrust will vary depending on **ALT**, **PTCH**, and **ROLL**.

When **ALT** reads 6000 m, stop engine. Restart engine at 10% thrust and increase **ENG** thrust to 6% below the previous balance thrust. Let **VELZ** drop to -30 m/s and adjust thrust to maintain this rate of descent.

Your LLV is now falling towards the lunar surface at -30 m/s (approximately 60 mph). You must slow the rate of descent or you will crash. (A descent rate as slow as -4 m/s will cause a disasterous impact.) Slow your descent so that **VELZ** is no more than -3 m/s. You will achieve a soft landing by gradually reducing **VELZ** as you approach the lunar surface.

Correct **ALT** and **VELZ** settings for soft landings are:

ALT	VELZ
6000 m	-40 m/s
3000 m	-30 m/s
1500 m	-20 m/s
500 m	-10 m/s
250 m	- 5 m/s
less than 250 m	- 3 m/s

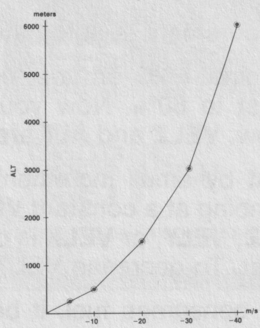


Figure 29: *Graph of soft landing; Altitude versus VELZ*

Adjust **VELZ** by decreasing or increasing thrust.

If you are within 20 seconds of crashing or if descent rate is very high and thrust is very low, a **HIGH RATE** warning will flash and sound in your cockpit until you establish a **VELZ** rate of between 3 m/s and -3 m/s. When you see a light (BLUE for Apple/ GREEN for IBM) in the upper left corner of your screen, and a flashing **LANDED** notification on your control panel, shut down the engine. To repeat this exercise, refuel your craft.

ANALYSIS: Even after the engine is shut down inertia continues to carry the LLV higher, though at a decreasing VELZ. VELZ decreases because the lunar craft is subject to the Moon's gravity. Gravitational forces cause the craft to decelerate. Thrust counteracts the Moon's gravitational pull.

Exercise 2: HOVERING

OBJECTIVE: Achieve an altitude of 6000 m. Descend to and then maintain hover at 30 m above the lunar surface. This exercise teaches techniques for maintaining the LLV at a constant altitude above a planetary surface by using thrust to reduce **VELZ** to 0 m/s.

DESCRIPTION: Hovering, the maneuver taught in this exercise, requires you to stop your descent at a specific altitude and maintain that altitude above the landing pad. This maneuver can save your life under circumstances involving unexpected obstructions on or near your landing site. This exercise does not involve pitch (forward/back motion) or roll (left/right motion). It concentrates on developing control of vertical motion (up/down along the Z axis).

Press **[G]** at the cockpit menu. Refuel your craft, ignite the engine, and increase thrust to 60%. Now reduce thrust to maintain **VELZ** of 20 m/s. When **ALT** reaches 6000 m shut down the engine and begin deceleration.

Restart the engine and quickly increase thrust to a rate 6% to 8% below balance thrust level. Let **VELZ** decrease to -30 m/s. Use fine thrust adjustments to maintain this descent rate.

As your craft slowly falls toward the lunar surface, gradually increase thrust so that when **ALT** is 100 m, **VELY** is -1 m/s. As you approach an **ALT** of 30 m, increase thrust. As soon as **ALT** stops decreasing reduce thrust to the balance thrust level. Make sure that the **ALT** reading does not begin to increase.

Now you should be hovering a few meters above the Tranquility Base landing pad. To maintain this position, use fine thrust adjustments to increase or decrease thrust rate. As your LLV's weight decreases due to fuel consumption, you must decrease thrust rate in order to maintain a constant position.

Now execute a soft landing. Reduce thrust slightly and wait until **VELZ** is -2 m/s. Return thrust to its previous balance level. Use fine thrust adjustments to achieve landing. Remember, a **VELZ** of -4 m/s or greater will result in a crash. Keep **VELZ** at -3 m/s or less.

Once you have landed, shut down your engine.

ANALYSIS: To maintain a stationary position above the lunar surface, a sufficient rate of thrust must be used to bring **VELZ** to a constant 0 m/s. This thrust rate varies according to your remaining fuel level - less fuel, less weight, less thrust. Thrust is used to counteract the force of gravity.

Exercise 3: MANEUVERING DURING HOVER

OBJECTIVE: While hovering at an altitude of 30 m, become familiar with **PTCH** and **ROLL** controls. **PTCH** controls horizontal (forward/back) rotation. **ROLL** controls lateral (left/right) rotation.

DESCRIPTION: The previous exercises concentrate on control of altitude, rate of ascent and descent, and thrust. This exercise adds horizontal and lateral motion, demanding control of pitch and roll.

From the cockpit menu, press **[G]**. Refuel your craft, ignite the engine, and achieve an **ALT** of 30 m. Roll to +5 deg.

When **VELX** is 1 m/s, return **ROLL** to 0 deg. Make sure to maintain a constant **ALT**. If the craft begins to drop, increase thrust slightly.

Notice that even though **ROLL** is 0 deg, your craft continues to move right at a rate of 1 m/s. Stop this inertial motion and return **VELX** to 0 m/s by rolling the craft to -5 deg. When **VELX** is 0 m/s, return **ROLL** to 0 deg.

Repeat the above maneuver with the **PTCH** controls. Pitch your craft to +5 deg. When **VELY** is 1 m/s, return **PTCH** to 0 deg. To stop your craft, move **PTCH** to -5 deg. When **VELY** is 0 m/s, return **PTCH** to 0 deg.

To return to your previous position, keep **PTCH** at -5 deg until **VELY** is -1 m/s. Now return **PTCH** to 0 deg. As you approach your previous **DIST** (distance), stop your craft by changing **PTCH** to +5 deg until **VELY** is 0 m/s, then return **PTCH** to 0 deg.

You can attempt a landing at any time during this exercise if **VELX**, **VELY**, and **VELZ** are at or between +3 m/s and -3 m/s. A landing at +3 m/s or -3 m/s (about 8 mph) may be a bit bumpy. A higher speed landing will result in a crash.

If you land within the perimeter of the Tranquility Base landing pad (**DIST** and **XRNG** of between +500 m and -500 m from the center of the pad), you can refuel the LLV for another flight. If you land outside the Base's perimeter, you cannot refuel. You must shut down your engine and return to the cockpit menu before beginning another flight.

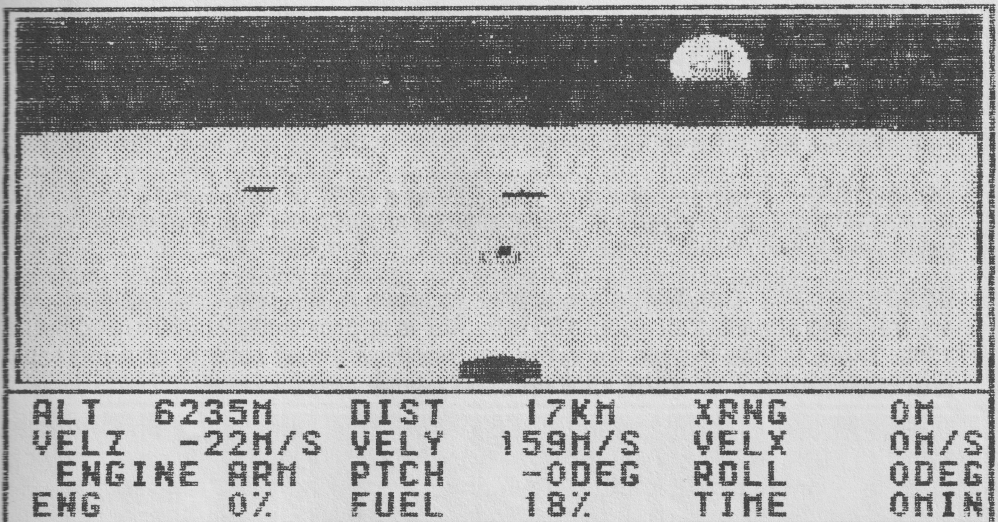
ANALYSIS: When you pitch or roll the LLV away from its vertical axis (**PTCH** 0 deg, **ROLL** 0 deg), a small percentage of **ENG** thrust is used to move the ship horizontally or laterally (forward/back or left/right). The LLV continues to move in a horizontal direction after **PTCH** or **ROLL** return to 0 deg until an approximately equal amount of force has been exerted in the opposite direction.

Exercise 4: LANDING FROM APPROACH

OBJECTIVE: Assume control of the LLV at a **DIST** between 10 km and 20 km from Tranquility Base. Your ship will be moving rapidly towards the landing pad at a **VELY** of about 130 m/s starting from an altitude of 5000 m. (**DIST**, **VELY**, and **ALT** are varied each time this exercise is repeated.) Your prime objective is to slow the LLV so that a soft landing can be executed.

DESCRIPTION: A successful landing requires quick decisions and smooth coordination at the controls. Your task is complicated by a limited fuel supply; you have only 18% fuel. There is little margin for error in this exercise. A single mistake could cost the lives of your passengers and the crew. The flight parameters have been set so that the LLV is aligned for approach to the landing pad. This exercise does not involve controlling **ROLL.**

Press **[A]** at the cockpit menu. The view from your cockpit window reveals the Earth hovering above the lunar horizon, several rifts and craters, and the Tranquility Base landing pad.



Ignite the engine and increase thrust to 22%. Bring **VELZ** to -30 m/s. Slowly adjust the thrust rate so that **VELZ** is no greater than -3 m/s when landing.

Look at your control panel:

> **VELY** is over 100 m/s
> **PTCH** is +22 deg

A portion of the engine thrust is slowing your forward motion due to the **PTCH** angle. To achieve a soft landing move **PTCH** toward 0 deg while adjusting your rate of descent. Ideally, when **VELY** reaches 0 m/s, **PTCH** should be at 0 deg.

Use the table below to guide **PTCH** adjustments during this exercise:

VELY	reduce PTCH to
40 m/s	15 deg
20 m/s	3 deg
10 m/s	1 deg
3 m/s	0 deg

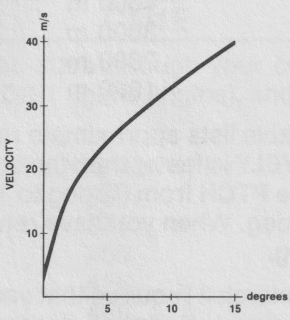


Figure 30: *Graph of pitch adjustments*

You must coordinate **PTCH** adjustment with engine thrust to reduce both forward and descending speeds. A perfect score on this exercise requires that you land within 500 m of the base. Because of the level of difficulty, passing marks can be achieved by simply landing your craft safely regardless of distance from the landing pad.

ANALYSIS: You should have mastered Exercises 1 through 3 before attempting this exercise. Engine thrust is used to counteract inertial and gravitational forces. Rapid responses are required to succeed in this exercise. Failure to respond quickly will result in overshooting the base or crashing. Remember that you have only a partial fuel supply (18%) when you begin this training exercise.

Exercise 5: BASE LANDING FROM APPROACH

OBJECTIVE: Assume control of your LLV at a **DIST** of between 10 km and 20 km from Tranquility Base. Achieve soft landing within the perimeter of the landing pad.

DESCRIPTION: Conditions are similar to those in the previous exercise. You are traveling at a **VELY** of about 130 m/s. **ALT** is approximately 5000 m and fuel is 18%. There is little margin for error. An incorrect thrust setting, or a too rapid reduction in **VELZ** or **VELY**, can result in failure.

Press **[A]** at the cockpit menu. Start your engine immediately and increase thrust to 22%. Adjust engine thrust to bring **VELZ** to -30 m/s. Use the following table to coordinate **VELY** and **PTCH** control.

DIST	TARGET VELY(m/s)	PTCH(deg)
15 km	142	22
14 km	120	22
13 km	116	22
12 km	111	22
11 km	106	22
10 km	100	22
9000 m	95	22
8000 m	88	22
7000 m	80	22
6000 m	71	22
5000 m	59	22
4000 m	45	15
3000 m	30	15
2000 m	17	3
1000 m	6	1

This table lists approximate rates. Mid-course adjustments may be necessary if your **VELY** is faster than the target **VELY** for a specified distance. If **VELY** is slow, reduce **PTCH** from 22 deg to 15 deg. If **VELY** is fast, increase **PTCH** from 22 deg to 30 deg. When you have returned **VELY** to the scheduled rate, adjust **PTCH** to 22 deg.

This exercise requires that you bring down your craft within the perimeter of the landing pad. If, during descent, your approach will set you down outside this perimeter, halt your descent. Hover and **PTCH** to adjust your approach.

When landing maneuvers are complete, return to the cockpit menu. To repeat this exercise, press **[A]** at the cockpit menu.

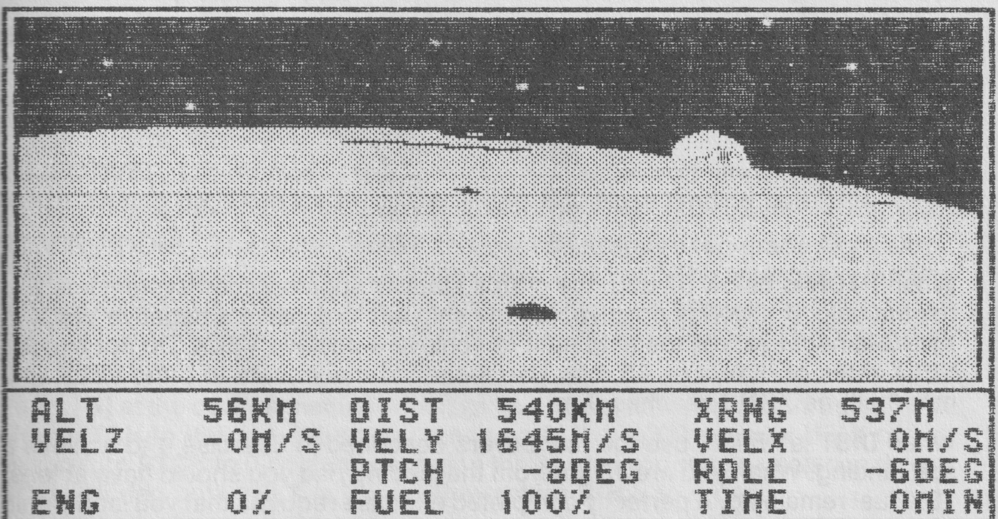
ANALYSIS: Every approach to the Tranquility Base landing pad is different. You must be able to adapt your landing procedures for each approach exercise. Using **PTCH** controls to vary both forward and downward braking force, you can achieve soft landing. Your greatest obstacle to success is your limited (18%) fuel supply. Approach the landing pad too slowly and you will exhaust your fuel supply; approach too rapidly and you will overshoot the pad or crash.

Exercise 6: DESCENT TO BASE FROM ORBIT

OBJECTIVE: Assume control of your LLV while in lunar orbit and achieve soft landing within the perimeter of the landing pad.

DESCRIPTION: This exercise requires mastery of the skills taught in Exercises 1 through 5. You begin descent with a 100% fuel supply. Coordinate adjustments in **PTCH**, **ROLL**, and **ENG** thrust to achieve a soft landing on target. You are put into a slightly different orbital position and speed each time you run through this exercise.

Press **[O]** at the cockpit menu. You are now viewing the Moon from a lunar orbit.



Move **PTCH** to 90 deg. You should be able to see stars through your cockpit window. Use the chart below to coordinate **VELY**, **DIST** (ignite engine), and **DIST** (engine thrust 100%).

VELY m/s	DIST (ignite ENG) km	DIST (ENG 100%) km
1500	370	350
1550	395	375
1600	420	400
1650	445	425
1700	470	450

Ignite engine when you have reached an appropriate distance. Increase thrust to 100% when you reach the next distance marker. As thrust reduces **VELY**, lunar gravity begins to pull your craft toward the Moon's surface. Your **VELZ** reading indicates increasing rate of descent.

Control panel readings during the initial phase of descent approximate the following:

VELZ(m/s)	VELY(m/s)	DIST(km)
-15	1370	300
-35	1230	250
-70	1060	200
-120	845	150

When **VELZ** passes -100 m/s, decrease **PTCH** to 80 deg, then 70 deg, then 60 deg. Pause for a moment at each **PTCH** reading. Use the **PTCH** adjustments to maintain a **VELZ** rate at or below -150 m/s. Less pitch means more energy is being exerted against the Moon's gravitational pull, slowing your rate of descent. Use **PTCH** to decrease **VELZ** to -100 m/s.

When **DIST** is 85 km and **VELY** is approximately 500 m/s, reduce **ENG** to 60% and **PTCH** to 45 deg. A lower thrust setting requires a lower pitch angle to keep your descent rate from increasing.

When **ALT** reads 10 km, begin your transition to approach. Reduce **VELZ** to approximately -40 m/s and descend to an **ALT** of approximately 6000 m.

When you have acheived a **VELZ** of -40 m/s, gradually reduce **PTCH** to 22 deg. Maintain **DIST** and **VELY** so that they approximate the following target rates:

DIST (km)	VELY (m/s)
70	420
50	320
30	210
20	155
15	125

When **PTCH** is below 37 deg, the craft's stability augmentation system lets you roll the ship. If **XRNG** is positive, roll the ship left to achieve a negative **VELX**. If **XRNG** is negative, roll the ship right to achieve a positive **VELX**. Do not exceed **VELX** rates of -5 m/s or +5 m/s. Use these roll maneuvers to bring **VELX** to 0 m/s (halt) as **XRNG** reaches 0 m.

When **DIST** is 15 km, use the manuevers described in Exercise 4 to achieve a soft landing. When you are 15 km from the landing pad you should have at least 18% fuel remaining. A perfectly completed exercise requires that you land within 500 m **DIST** and **XRNG** in the center of the pad. If you land within the landing pad's perimeter, you can refuel and begin another flight. If you have over- or undershot the landing pad, you must return to the cockpit menu before you make another attempt.

ANALYSIS: In general, a high thrust rate for a short period of time uses less fuel than a lower thrust rate for a longer period of time. Therefore, igniting the engine and increasing thrust to 100% when you are as close as possible to the landing pad leaves you with more fuel for use during the difficult approach maneuvers. High speed approach, however, is more difficult to control than a lower speed approach. If you wait until **DIST** is less than 350 km, then ignite the engine and increase thrust to 10 %, you run the risk of overshooting the landing pad.

Exercise 7: LIFTOFF

OBJECTIVE: Assume control of the stationary ship, achieve liftoff and a successful lunar orbit.

DESCRIPTION: You must achieve a velocity at least equal to the Moon's orbital velocity. **VELY** must exceed 1600 m/s and **VELZ** should be nearly 0 m/s. A circular orbit will return you to Tranquility Base in about two hours.

Press **[G]** at the cockpit menu. Refuel your ship and ignite the engine. Increase thrust to 100%. Move **PTCH** to -60 deg.

As you approach orbital velocity (**VELY** is 1600 m/s), gradually increase **PTCH** to -90 deg. When **VELY** exceeds 1600 m/s, shut down the engine. If your ship begins to descend, restart the engine and increase thrust until orbital speed increases enough to stop descent.

ANALYSIS: This training simulation will not allow you to exceed the altitude limit (300 km for Apple/6500 km for IBM) above the lunar surface. If your orbit exceeds the limit, you are returned to the cockpit menu. If you have achieved a circular orbit, you will return to the landing pad site in about two hours. You will not have enough fuel to attempt a landing. To refuel, return to the cockpit menu and then return to orbit by pressing **[O]**.

Exercise 8: FLIGHT TO EMERGENCY LANDING PAD

OBJECTIVE: Lift-off from Tranquility Base, execute soft landing at the emergency landing pad, and return to the Tranquility Base landing pad.

DESCRIPTION: The maneuvers in this exercise require top grade flight skills. Timing must be precise and calculations must be exact. The emergency landing pad is located at a **DIST** -65 km and **XRNG** 1000 m. An error in the initial leg of this flight can result in excessive fuel consumption. You will not have enough fuel to make it back to Tranquility Base.

Press **[G]** at the cockpit menu. Refuel, ignite engine, and increase thrust to 70%. Move **PTCH** to -60 deg. When you reach an **ALT** of 1000 m and a **VELY** of 200 m/s, return **PTCH** to 0 deg and decrease thrust until you reach a balance thrust. **ROLL** +5 deg until **VELX** is 3 m/s. Now return **ROLL** to 0 deg.

As **ALT** reaches -45 km, begin preparing for landing at the emergency landing pad. Move **PTCH** to about 30 deg and increase thrust so that **VELY** decreases to 5 m/s as **DIST** approaches -65 km. Watch **ALT** and **VELZ** carefully. If **VELZ** reaches -10m/s and **ALT** drops below 500 m, increase thrust to slow descent. As **XRNG** approaches 1000 m, decrease **VELX** to 0 m/s.

As you approach the emergency landing pad, watch out for the large radio dish antenna. A collision with the antenna will be fatal.

If you land within 100 m of the emergency landing pad, you can refuel. Use the previous instructions to return to Tranquility Base. Increase thrust to lift-off. Set a course for the Base by quickly moving **PTCH** to 60 deg. Remember, if you

choose not to refuel, your ship will be lighter than when you began your flight due to fuel consumption. Maneuvers will require less thrust to increase **VELY** and **VELZ**. Balance thrust also will be less.

There is little margin for error in your approach to Tranquility Base. Overshoot the Base, decrease **VELY** too quickly, miscalculate direction, and your fuel supply will be exhausted before you can execute a soft landing.

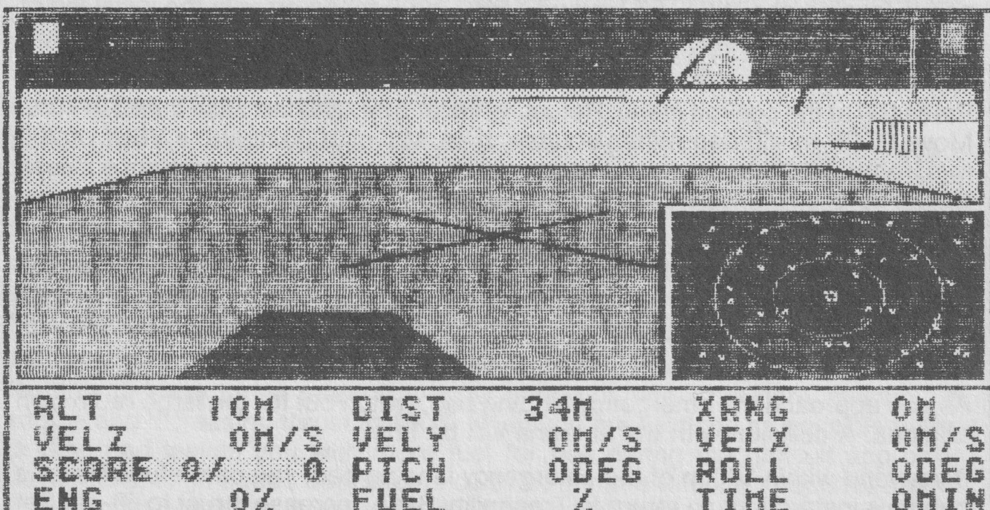
ANALYSIS: This exercise is the ultimate test of flight maneuver mastery. Fuel is your most critical problem. Spend too much time in the initial leg of the flight and you will not have enough fuel to get back to Tranquility Base. Lunar Mining Facility pilots have discovered that a higher thrust rate over a shorter period of time uses less fuel than burning the engine at a lower thrust rate for a longer time period.

Cargo Run Mission

If you have successfully accomplished all the previous exercises and displayed mastery in each aspect of flight control, your training is complete. You are now a Lunar Landing Vehicle pilot.

Your first assignment is as part of the Transport Unit of a Mobile Mining Team. Your team has left canisters of lunar ore in the vicinity of Tranquility Base. Each canister is fitted with a small transponder which sends a signal that is visible on your radar screen. Your job is to collect the ore canisters and transport them to the Base. Your mission rating depends on the accuracy of landings and the number of canisters loaded during each cargo run.

To begin your cargo run mission press **[C]** at the cockpit menu. Turn on the radar display by pressing **[D]**. To turn off the radar display, simply press **[D]** again. Fueling bases appear as squares; ore canisters appear as colored dots. The **V** in the center of the radar display indicates the field of view from your cockpit window.



When you locate an ore canister, manuever your LLV into landing position. You should be able to see the canister in front of your ship. To load the canister, you must land within 100m distance and your engine must be shut down. Press **[L]** to load the ore canister.

Your mission rating is displayed on the instrument panel as **SCORE** C/P. C represents the number of canisters on board your ship during a particular run; as each canister is added to your cargo, C increases by 1. P represents the cumulative number of points awarded for the accuracy of ore canister retrieval. You can receive from 1 to 10 points for each canister pick-up; the closer you land to the canister, the higher the number of points awarded.

Keep a close watch on your fuel level. Remember, you still have to return to Base. All the forces and conditions you encountered during flight training apply in these actual missions. Each ore canister has a mass equal to 10% of a full fuel load. Use the knowledge and skills you acquired in the Training Exercises to determine the number of canisters you can collect and still return to Tranquility Base.

When you have landed at the Base, shut down your engines. To unload your cargo and refuel your LLV, press **[R]**. When the canisters are unloaded, the C part of your score returns to 0; P is not reset to 0 when cargo is unloaded. The amount of fuel your ship takes on depends on the number of canisters you successfully return to the Base. For every canister returned to Tranquility Base, your ship will automatically receive a 20% increase in fuel (up to 100%).

Your cargo run mission will continue until you press **[ESC]** or crash your LLV.

Solo Flight Excursions

The Flight Exercises provide training in the kinds of maneuvers necessary for controlling your LLV. Once you have confidence in your piloting abilities, you can investigate the Moon and its surrounding environment on your own.

Your travels can take you to the original Apollo 11 landing site which is between 15 km and 20 km from the Tranquility Base landing pad. While in LLO inspect the base from above, or land next to the Tranquility Base domes and get another perspective on your "home away from home." When you've mastered low altitude flight, skim across the surface of the Moon and observe rilles, craters, and other topographical features.

Although regulations strictly forbid aerobatics, you might want to test yourself by flying loops around the Base radio antenna or by buzzing the housing domes.

APPENDIXES

Appendix A: LLV CRAFT CONTROLS
Appendix B: GLOSSARY
Appendix C: THE PHYSICS OF SPACE FLIGHT
Appendix D: THE MOON
Appendix E: ASTRONAUT/COLONIST QUALIFICATIONS
Appendix F: USING Lunar Explorer IN THE CLASSROOM
Appendix G: SOURCES and ADDITIONAL READING

Appendix A: LLV CRAFT CONTROLS

Keyboard Controls

Vehicle Orientation Controls

/ /, / /+	/ /e, / /c IBM		
[I]	**[↑]**	- PTCH	pitch forward; window down
[M]	**[↓]**	+ PTCH	pitch back; window up
[J]	**[←]**	- ROLL	bank left
[K]	**[→]**	+ ROLL	bank right

Engine Thrust Controls

Apple	IBM	
[0]	*	sets increment of change in thrust at 10%
[2]	*	sets increment of change in thrust at 2%
[+] †	**[+]** †	increases thrust
[-]	**[-]**	decreases thrust

* IBM engine thrust increment is always 1%

† It is not necessary to press **[SHIFT]**

Cockpit Controls

Apple/IBM	
[D]	view self-running demonstration
[G]	begin flight at the Tranquility Base landing pad (Exercises 1, 2, 3, 7, and 8)
[A]	begin flight in approach to Tranquility Base (Exercises 4 and 5)
[O]	begin flight in lunar orbit (Exercise 6)
[C]	begin cargo run mission

Additional Controls	
Apple/IBM	
[R]	refuel. Engine must be shut down; craft must be within landing pad perimeter. Also unloads ore canisters in cargo run mission
[E]	arm engine (if fuel is onboard) at 10% thrust. If engine is armed, pressing **[E]** shuts down engine
[ESC]	return to cockpit menu. May be used at any time during flight
[SPACEBAR]	pause flight. Press any LLV control key to resume flight
[D]	toggle radar display
[L]	load ore canisters

Joystick Controls

Joystick **FORWARD**	- PTCH	pitch forward; window down
Joystick **BACK**	+ PTCH	pitch back; window up
Joystick **LEFT**	- ROLL	bank left
Joystick **RIGHT**	+ ROLL	bank right

Instrument Panel

ALT	altitude in meters (m) or kilometers (km)
DIST	horizontal distance from landing pad in meters (m) or kilometers (km)
XRNG	lateral distance in meters (m) or kilometers (km); + right, - left
VELZ	vertical speed in meters per second (m/s); + up, - down. VELZ affects ALT
VELY	horizontal speed in meters per second (m/s); + forward, - back. VELY affects DIST
VELX	lateral speed in meters per second (m/s); + right, - left. VELX affects XRNG
PTCH	angle of the ship around the lateral axis in degrees (deg); + window up, - window down. PTCH affects VELZ and VELY
ROLL	angle of LLV around the horizontal axis in degrees (deg); + right, - left. ROLL affects VELZ and VELX
ENG	engine thrust in % (from 0% to 100%)
FUEL	remaining fuel in % (from 0% to 100%)
TIME	elapsed engine burn time in minutes (min). Clock starts when engine is armed

Lights and Messages

(Colors vary depending on hardware configurations)

Apple	IBM	
BLUE flashing	GREEN flashing	nearing lunar surface
BLUE steady	GREEN steady	landed
ORANGE flashing	RED flashing	fuel below 12%
VIOLET flashing	MAGENTA steady	limit of roll capability
VIOLET steady	BLUE steady	roll disabled due to high PTCH angle
ORANGE flashing	MAGENTA steady	limit of pitch capability

ENGINE ARM	engine is shut down. Arm engine by pressing **[E]**
DEMO MODE	automatic demonstration is running
HEIGHT LIMIT	craft is approaching maximum altitude (ALT 300 km for Apple version/ 6500 km for IBM version); you will be returned automatically to the cockpit menu
HIGH RATE	you are within 20 seconds of crashing or velocity is very high and altitude is very low
LANDED	successful landing
PAUSE	flight halted. To resume flight press any LLV control key
SCORE C/P	score during cargo run mission. C=number of canisters on board; P=total mission score

Appendix B: GLOSSARY

ACCELERATION	rate at which velocity changes with time. A vector quantity, its magnitude is usually measured in meters per second squared (m/s^2)
ALTITUDE, ALT	height, measured in meters (m) or kilometers (km), above the lunar surface
ANORTHOSITE	a type of igneous rock, lighter colored and more silica-rich than basalt, common in the lunar highlands and used to manufacture aluminum
ATTITUDE	rotational position along the horizontal (Y), lateral (X), or vertical (Z) axis. Attitude is determined by PTCH and ROLL
APOLLO PROGRAM	the U.S. program to land humans on the Moon, 1961-1972; first landing July 20, 1969
ASTROMETRY	the study of positions and motions of the stars
AXIAL	along the main axis of rotation, or the axis running forward, as perceived from within a rotating body
AXIS	a line through a body around which that body rotates
BALANCE THRUST	engine thrust required to maintain a constant vertical velocity (VELZ) when pitch and roll are at 0 degrees
BANK	rotation around the axial direction either left or right. See ROLL
BASALT	a type of igneous rock, often formed in lava flows, common on the Moon and Earth
BASIN	large impact crater on the Moon, usually several hundred km across, flooded with basaltic lava, and surrounded by concentric rings of faulted cliffs
BURN	to fire or ignite engines. Accomplished by pressing [E] when LLV engine is shut down
CENTRIFUGAL FORCE	an inertial force tending to pull a revolving mass outward from the center of its orbit

CIRCULAR VELOCITY	velocity of an object in circular orbit, measured with respect to the center of mass of the orbiting pair
CONSTELLATION	imaginary pattern found among stars, resembling animals, mythical heroes, etc.; different cultures map different constellations
CORE	the densest inner region of the Earth or Moon, probably of nickel-iron composition
CRATER	see impact crater, volcanic crater
CRUST	the outermost solid layer of a planet, with composition distinct from the mantle, and defined by a seismic discontinuity
DELTA V	velocity change, or acceleration
DIST	horizontal distance from landing pad measured in meters (m) or kilometers (km) along the Y axis
ESCAPE VELOCITY	minimum speed required for an object to escape permanently the gravitational field of a planet or moon
EVAPO-TRANSPIRATION	loss of water from soil both by evaporation and by transpiration (emission of water from the surface of plant parts)
FABRICATION SPHERE	a space facility located alongside the space habitat. It is the site for manufacturing, assembly, and construction
FORCE	in physics, a specific phenomenon producing acceleration of mass. Forces can be generated in many ways, such as by gravity or by rocket engine exhaust
FREE FALL	motion under the influence of gravity only, without any other force or acceleration such as engine thrust
FUEL CELL	an electro-chemical generator in which the chemical energy from the reaction of an oxidizer and a fuel is converted directly into electricity
G	force of the Earth's gravity, approximately 9.8 m/sec^2 (32 ft/sec^2) in terms of acceleration
GIMBAL (NONGIMBAL)	(noun) a device with two perpendicular and intersecting axes of rotation on which an engine can be mounted and swiveled in two directions; (verb) to swivel a motor in order to change the angle of the engine
GRAVITY	the force by which all masses attract all other masses
HOVER	maintain a constant altitude
HLLV	Heavy Lift Launch Vehicle. A large transport used for ferrying personnel and cargo from Earth to Low Earth Orbit (LEO).
IMPACT CRATER	a roughly circular depression of any size (known examples from microscopic to diameters greater than 1,000 km) caused by impact of a meteorite

INERTIA	the property of motion described by Newton's First Law of Motion. That is, a body at rest remains at rest and a body in motion moves at a constant speed in a straight line unless a net force acts on it. See Appendix C.
INERTIAL MEASUREMENT UNIT, IMU	subsystem which, by using gyroscopic devices and a computer, automatically determines spacecraft attitude and location without reference to external sources
IOTV	Inter-Orbital Transport Vehicle. The workhorse of the colony transport system, this craft carries personnel and cargo between points in space. It never lands on any planetary body.
KILOGRAM, kg	2.2 pounds. This quantity is not a mass unit but represents the fact that a kilogram is a mass that weighs 2.2 pounds under standard conditions of gravity where $g=9.8\ m/s^2$
KILOMETER, km	1,000 meters; 0.6214 mile
KILOPASCAL, kPa	.145 pounds/in^2. A measure of pressure
LANGRANGIAN LIBRATION POINTS	Five points in the Earth-Moon system surrounded by shallow valleys of gravity. These valleys arise from a balancing of the gravitational attractions of Earth and Moon with the centrifugal force in the rotating coordinate system of Earth and Moon. Principle feature of these locations in space is that a material body placed there maintains a fixed relation with respect to Earth and Moon as the entire system revolves around the Sun.
L_5	Langrangian libration point 5; location of DAKOTA Space Habitat.
L_2	L_1, L_2 (location of Mass Catcher), and L_3 are saddle-shaped valleys and are unstable. L_4 and L_5 are bowl-shaped and are stable. A body displaced in any direction at these two points returns to the center. Both are located on the Moon's orbit at equal distances from both the Earth and the Moon
LEO	Low Earth Orbit
LLO	Low Lunar Orbit
LLV	Lunar Landing Vehicle. Principle transport from LEO to lunar surface and from Tranquility Base to other locations on the Moon.
MANTLE	a region of intermediate density surrounding the core of a planet
MARE, MARIA	a dark-colored region on a planet or satellite; a region of basaltic lava flow on the Moon
MASS	material; the amount of material. Measured in kilograms (kg) or tons (t)

MASS CATCHER	a kind of automated "catcher's mitt" orbiting at L_2 for collecting lunar material launched by the mass driver. A part of the delivery system at the Tranquility Base Mining Facility
MASS DRIVER	an electromagnetic mass accelerater used to propel small payloads of lunar material into space. A part of the delivery system at the Tranquility Base Mining Facility
METEORITE	an interplanetary rock or metal object that strikes the ground
METER, m	39.37 inches; 3.281 feet
m/s	meters per second; 1 m/s = 2.237 mph. The distance in meters a vehicle can travel in a one second time period
NEWTON	0.2248 pounds (under standard conditions of gravity). A measure of force named for Sir Isaac Newton. 1 newton can move 1 kilogram of mass at an acceleration of 1 meter/second^2
NEWTON'S LAW OF GRAVITATION	states that the force of gravity at any distance from a given mass varies as the inverse square of the distance
NEWTON'S LAWS OF MOTION	three rules describing motion and forces. Briefly, (1) a body remains in a state of motion unless a force acts on it; (2) force equals mass times acceleration; (3) for every action there is an equal and opposite reaction
ORBIT	unpowered motion around a central object or force field
PITCH, PTCH	the attitude movement of a spacecraft where the nose tips up or down, rotating around the X (lateral) axis. Controlled by [↓] (window up) and [↑] (window down) or joystick forward (window down) and joystick back (window up)
POSITION	location of the LLV with respect to the landing pad. Position along the X, Y, and Z axes is determined by XRNG, DIST, and ALT, respectively
QUAD	a four-engine package used to control the LLV's rotation
RADIATOR	structure with a large surface area for dispersing waste heat
REGOLITH	a powdery soil layer on the Moon, caused by meteorite bombardment
ROLL	rotation, either left or right, around the Y (horizontal) axis. Controlled by [←] and [→] or moving joystick left or right.
ROTARY PELLET LAUNCHER, RPL	propulsion device used to position the mass catcher so that it always faces the incoming stream of payloads shot from the mass launcher
SATELLITE	any small body orbiting around a larger body

SMF	Space Manufacturing Facility
SOLAR CELL	(photovoltaic cell) device used to convert the radiant energy of sunlight into electric power
SOLAR WIND	outrush of ionized gas particles constantly emitted by the Sun in all directions. Near Earth solar winds travel at velocities of 600 km/sec
SOLAR SYSTEM	the Sun and all the bodies orbiting around it
SSME	Space Shuttle Main Engine
STAR	a mass of material, usually wholly gaseous, massive enough to initiate (or to have once initiated) nuclear reactions in its central regions
TERMINATOR	the dawn or dusk line separating night from day on a planet or satellite
TERRA, TERRAE	the light-colored hilly highlands on the Moon
THRUST	the force generated by a high-speed discharge, as from a rocket
TIDE	a bulge raised in a body by the gravitational force of a nearby body.
TON, t	1000 kg. A measure of mass
TORUS	tube bent into a circle to form a wheel-like structure. The DAKOTA Space Habitat is constructed in this form
TRAJECTORY	a flight path traced by a spacecraft
VECTOR	a physical quantity (eg. velocity) with both magnitude and direction. Magnitude components are measured along the X, Y, and Z axes (eg. VELX, VELY, VELZ)
VELOCITY	rate at which distance changes with time. A vector quantity, velocity's magnitude is speed and is measured in meters per second (m/s)
VELX	left (-) or right (+) component of velocity measured in meters per second (m/s). VELX affects XRNG
VELY	forward (+) or backward (-) component of velocity measured in meters per second (m/s). VELY affects DIST
VELZ	upward (+) or downward (-) velocity measured in meters per second (m/s). VELZ affects ALT
X AXIS	axis of lateral (left/right) motion
XRNG	lateral distance along the X axis measured in meters (m) or kilometers (km)
Y AXIS	axis of horizontal (forward/back) motion
Z AXIS	axis of vertical (up/down) motion

Appendix C: THE PHYSICS OF SPACEFLIGHT

The history of spaceflight predates Wernher von Braun's aeronautical experiments (which led to the German V-2 rocket and the American space program), Robert Goddard's work with small rockets in the 1920s, and even Jules Verne's fanciful stories of enormous cannons propelling man into space. The ideas that made spaceflight possible were formulated during the years of the Black Death that wiped out half of Europe's population.

When the bubonic plague paralyzed England in 1665, twenty-two year old Isaac Newton left Cambridge University to carry on his studies at his home in Lincolnshire. During eighteen months of rural isolation, Newton almost single-handedly devised differential and integral calculus, discovered the composition of white light, invented the reflecting telescope, and began to define how gravity works. Newton's laws of gravity and motion are the foundations of what we call Newtonian physics. These are the principles on which modern spaceflight is based.

The Law of Universal Gravitation

As the story goes, Newton was inspired by an apple that fell from a tree while he sat in his garden speculating on the power of gravity. Newton observed that the Moon does not travel in a straight line, but follows a path curved around the Earth as though it were attracted to the Earth by some force. Force is what causes a mass to accelerate.

Acceleration is a change in velocity. Velocity has two components: speed and direction. Quantities that have both magnitude and direction are called vectors. Acceleration is a vector; a change in speed (magnitude) and direction. A familiar example is a car accelerating from 30 miles per hour to 50 miles per hour.

Objects near the Earth's surface fall at an acceleration of about 32 feet (9.8 meters) per second per second. That is, for every second that the object falls, its falling speed increases by another 32 feet per second. If you drop a stone from a 144 foot high tower, one second later the stone will be falling at a speed of 32 feet per second. After another second, its speed will have increased by another 32 feet per second to 64 feet per second. At the third second, when it strikes the ground, it will have accelerated to 96 feet per second (Figure 31). By dropping two stones of different sizes from a tower, Galileo demonstrated that all masses at the same place are attracted to the Earth with the same acceleration.

When a car turns a corner it accelerates away from the direction in which it was originally heading, even though its speed may remain the same. This example illustrates the direction component of the definition of acceleration. Acceleration is "change in velocity," and is therefore a change in speed and/or direction. As a moon orbits a planet it is constantly accelerating toward the planet (Figure 32). Newton realized that he could calculate from the Moon's known orbital motion, how fast it "fell way" from the straight line that it would have traveled if there were no force pulling on the Moon. Then he could compare the Moon's rate of acceleration away from the hypothetical straight line to the acceleration of an object falling toward Earth.

Newton found that the Moon, which is 60 times farther from the Earth's center than is an object at the Earth's surface, accelerates away from a straight path at only about 1/3600 (or 1/(60x60)) times the acceleration rate of an object falling

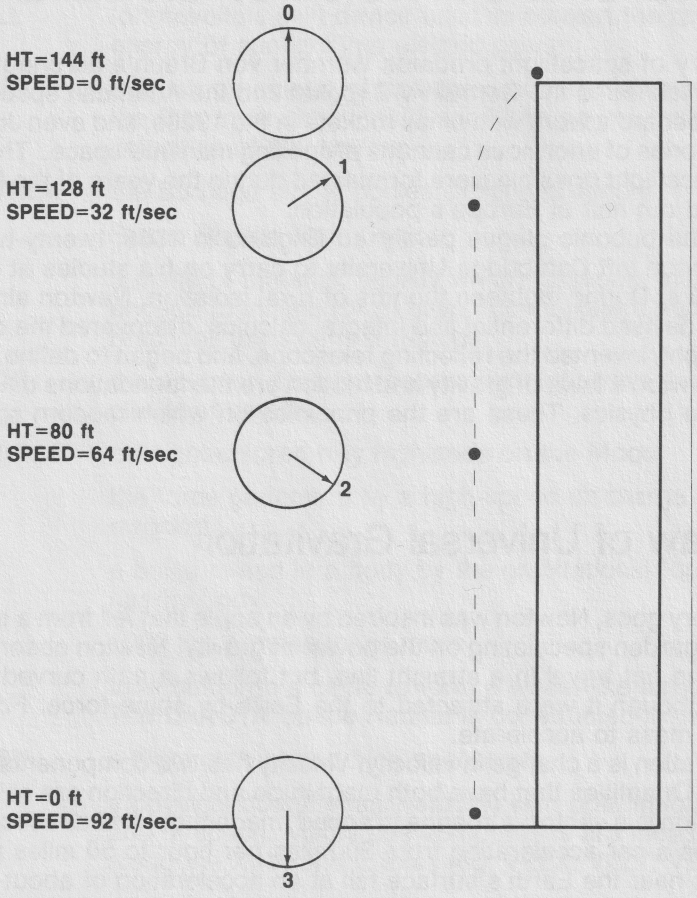


Figure 31: *Acceleration due to gravity. 32 ft/sec²*

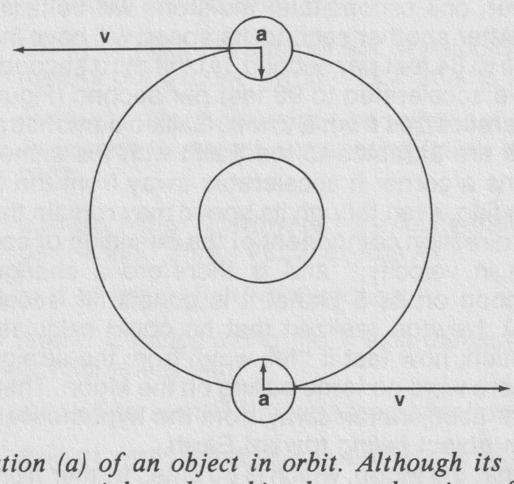


Figure 32: *Acceleration (a) of an object in orbit. Although its velocity (v) is in a direction tangential to the orbit, the acceleration of the object is in a direction towards the center of the orbit, resulting in a circular orbit*

near the Earth's surface (Figure 33). The force of the Earth's gravity on a body, therefore, diminishes as the inverse (the "1/" part of the fraction) square (the "(60x60)" part of the fraction) of the distance of the body from the Earth.

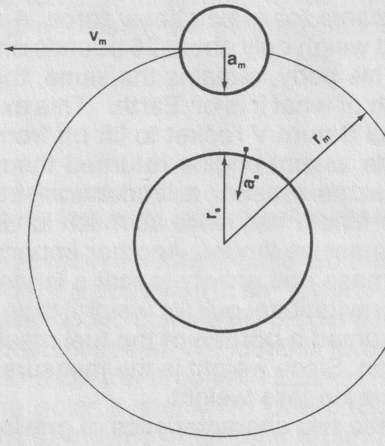


Figure 33: *Acceleration of the Moon versus acceleration of a stone. The distance of the Moon from the Earth's center (r_m) is 60 times the distance of the stone from the Earth's center (r_s). However, the acceleration of the Moon towards the Earth's center (a_m) is only 1/3600 that of the stone's (a_s)*

Like radio waves that grow weaker as you travel away from a station's transmitter, the force of gravity weakens as you travel farther from the source of gravity. This has important implications for spaceflight. An LLV hovering 1700 kilometers above the surface of the Moon has a quarter of the gravity to fight against than does a lander hovering only a few feet above the Moon. The first vehicle is twice as far from the Moon's center (source of gravity) as is the second vehicle (Figure 34).

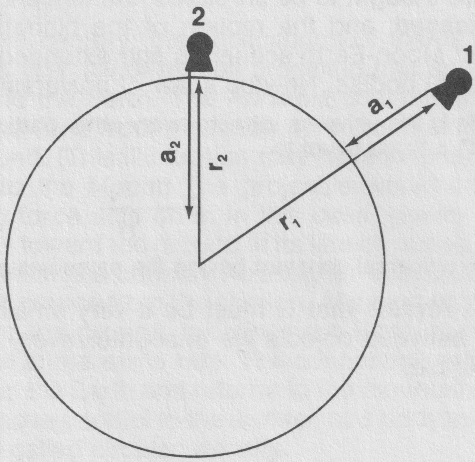


Figure 34: *At an altitude of 1700 miles, the LLV $_1$ is twice as far from the Moon's center as is LLV $_2$ (which is near the Moon's surface). But LLV $_1$ experiences only 1/4 of the acceleration due to gravity as that experienced by LLV $_2$*

Newton also discovered that gravitational attraction between two bodies is proportional to the amount of material, or mass, in each body. The more mass, the greater the attraction. If either mass doubles, then the gravitational force between them doubles. However, mass should not be confused with weight. Weight is merely another name for gravitational force. A man who weighs 150 pounds on the Earth would weigh only about 26 pounds on the Moon. His mass, the amount of material in his body, remains the same, though his acceleration has decreased to one-sixth of what it is on Earth. This explains why the Apollo flights needed the powerful Saturn V rocket to lift off from Earth, while a much less powerful lunar module ascent engine returned them from the much less massive Moon. For this same reason, a lander constructed from twice the material as that of another lander has twice as much lunar gravity to overcome as does the second less massive lander. Another important demonstration of the relationship between mass and gravity is that a lander with a half-capacity load of fuel is under less gravitational pull (or weight) than when it has a full fuel supply. The ship has consumed a portion of the fuel mass so that there is less mass for gravity to act upon. Since weight is the measure of gravitational force on mass, less mass will create less weight.

Newton put together these two characteristics of gravitational force: that it is proportional to the masses of two bodies, and inversely proportional to the distance between their centers. These facts define one law of gravitation. In mathematical terms:

$$F \text{ is proportional to } \frac{Mm}{r^2}$$

Where: F = gravitational force of attraction between two bodies
M = mass of larger body
m = mass of smaller body
r = distance between centers of M and m

Newton linked together two aspects of a single problem that, since the time of the Greeks, were thought to be unrelated: the tendency of objects to fall to the Earth when released, and the motion of the planets. Newton went beyond object-Earth and Moon-Earth scenarios and extended his law of gravitation to include all physical bodies. Newton's law of universal gravitation states that

> every particle in the universe attracts every other particle along the line joining the particles with a force equal to
>
> $$G\frac{m_1 m_2}{r^2}$$
>
> Where: G = universal constant having the same value for all pairs of particles.

Common sense reveals that G must be a very small value. The gravitational forces exerted between objects we encounter every day are, for all practical purposes, negligible.

Newton's Three Laws of Motion

Newton's masterwork *Principia Mathematica* is an investigation into mechanics (the study of the motion of objects) as well as a treatise on gravity. Mechanics is

the oldest of the physical sciences and its scope covers the microscopic collisions of molecules to the complex construction of galaxies. In *Principia*, Newton concentrated on describing an aspect of mechanics called dynamics, or the causes of motion. Newton's three laws of motion are fundamental postulates from which a host of phenomena can be predicted and observed.

The First Law

> Every body persists in its state of rest or of uniform motion in a straight line unless it is compelled to change that state by forces impressed upon it.

Before Newton's time, most scientists believed that some force was needed to keep a body in motion. If a body was in its "natural state" when it was at rest, then some external agent had to continually propel a body in order for it to move in a straight line at a constant speed. Without this force, it would "naturally" stop moving. This belief was a central argument against Nicholas Copernicus' Sun-centered model of the solar system. No one could imagine a force strong enough to keep the Earth moving in an orbit around the Sun.

Newton's first law of motion dispels the idea that force is required to keep a body in motion. This first law of motion is often restated as

> A body at rest stays at rest and a body in motion moves at a constant speed in a straight line unless a net force acts on it.

This law describes the property of motion called inertia. Inertia keeps the Earth in motion. In fact, the force of the Sun's gravity prevents the Earth from flying off into interstellar space.

As a Tranquility Base pilot you must contend with inertia. Once you orient the ship in a specific direction and fire your main engine, you travel along a straight line in that direction until the Moon's gravitational force drags you down or until you redirect your craft along a different heading. Overcoming inertia is a constant challenge to an LLV pilot.

Even in the seventeenth century, the implications of inertia for spaceflight were observed. Newton's first law of motion predicted that an object could be launched into orbit around the Earth. The *Principia* contains a diagram of an Earth satellite. It was to be fired from a cannon on a mountaintop, the cannon barrel parallel to the ground. (This illustration may have inspired Jules Verne's 1865 story *From Earth to the Moon*.) The projectile would continue moving forward until a modifying force acts on it. In this case, gravity (the modifying force) pulls the cannonball toward the ground. If its launch speed is too slow, the cannonball falls to Earth near the cannon. At a higher speed, it travels farther and will land at a greater distance from the cannon. At a high enough speed, the cannonball curves toward the ground, but since the Earth is round, it curves away from the cannonball at the same rate. The cannonball never reaches the ground, but travels around the Earth and returns to the mountaintop. The speed at which an object must move parallel to the surface of a body in order to stay in circular orbit around it is called circular velocity.

The farther an object is from Earth (or other body), the weaker the force of gravity that object must overcome, and therefore the lower the circular velocity. This is an important lesson for a Tranquility Base pilot. You can keep your lander aloft without sacrificing horizontal velocity by pitching your engine so that it is parallel to the ground and accelerating to the Moon's circular velocity, which is about 1680 meters per second (Figure 35).

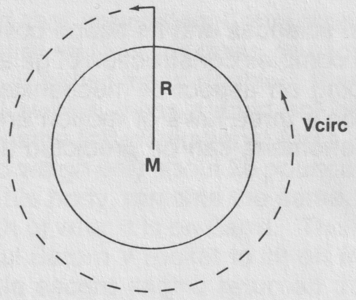


Figure 35: *Calculating the Moon's circular velocity*

The Second Law

> For every force acting on a body, there is a corresponding acceleration proportional to and in the direction of the force, and inversely proportional to the mass of the body.

In our discussion of gravity, we defined force as that which accelerates a mass. Newton defined force more precisely in his second law: For every force acting on a body, there is a corresponding acceleration proportional to and in the direction of the force, and inversely proportional to the mass of the body. In mathematical terms:

$$F = ma$$

Where: F = the sum of all forces acting on the body
m = the mass of a body
a = the acceleration of a body

When the *Lunar Explorer* LLV is in motion it is affected by at least two forces: thrust (the force of its engines) and gravity. Whenever several forces act on a body, each produces its own independent acceleration. The acceleration of the body is the sum of the independent accelerations. The acceleration due to gravity is always in a vertical direction, towards the center of the Moon. But in what direction does the engine force accelerate the craft?

Actually, there are three directions to the engine's acceleration: one is vertical (up/down); one is lateral (left/right); and one is horizontal (forward/back). Distribution of the acceleration depends on the craft's pitch and roll angles. When pitch and roll are 0 deg, the LLV is upright with respect to the Moon's surface and the engine is pointed downward. All of the engine's acceleration is directed vertically.

As you pitch the LLV forward, it loses some vertical acceleration in favor of horizontal acceleration. This means that less of the engine's force is used for overcoming gravity and more is used for moving horizontally across the surface of the Moon. At a pitch of -45 deg, half the engine's force is used for accelerating vertically (upward), and half is used for accelerating horizontally (forward). When the LLV is pitched at -90 deg, it is in a horizontal position parallel to the Moon's surface. All of its acceleration is exerted along the horizontal axis; none on the vertical axis (Figure 36). The same holds true for roll. When you roll the craft to one side or the other (left or right), vertical acceleration is decreased in favor of lateral acceleration.

The lesson to be learned is: when you roll or pitch your ship in order to navigate across the Moon's surface, remember that you sacrifice some of the engine force (thrust) that would have been used to overcome gravitational attraction.

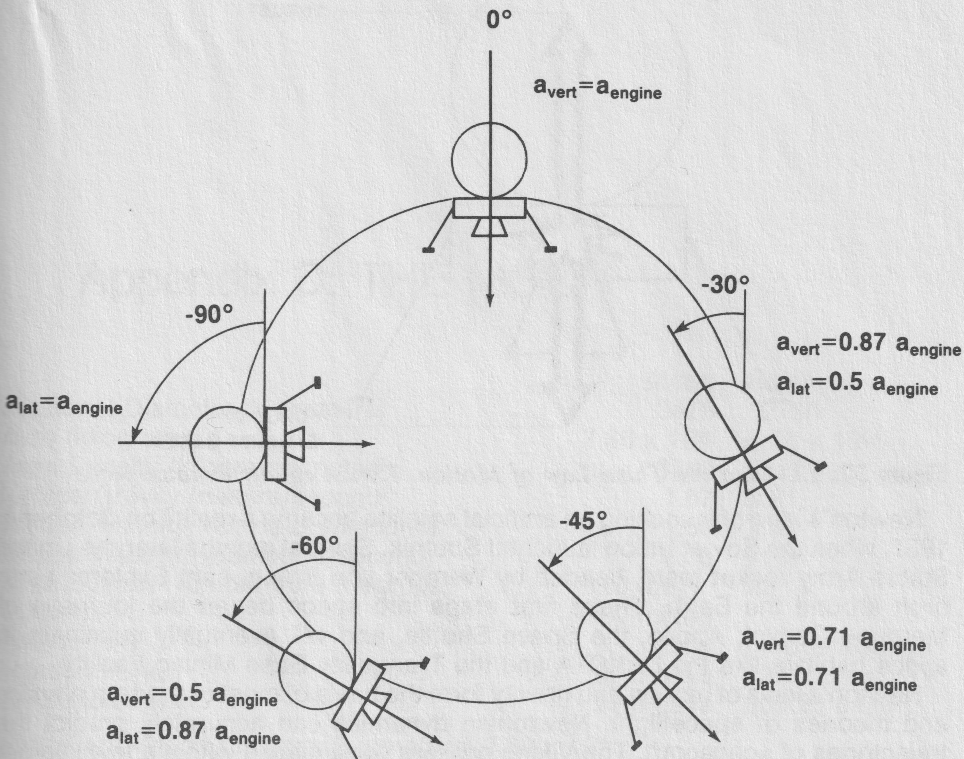


Figure 36: *Pitch angles distributing engine accleration (a eng) to vertical acceleration (a vert) and horizontal acceleration (a horiz)*

The Third Law

For every force (action) on one body, there is an equal and opposite force (reaction) acting on another body.

Newton's third law of motion is perhaps the most important to spaceflight. The cannon, described in the discussion of the first law of motion, is an impractical means of launching a body into Earth orbit. No shell could be accelerated to circular velocity (8 km/sec, or nearly 18,000 mph) within the length of a cannon barrel without shattering. Even if such an invulnerable shell could be constructed, the air resistance of the Earth's atmosphere would slow the shell, dragging it down to the ground.

Real spacecraft must carry their own means of propulsion and be able to operate in the vacuum of space. Rockets, used in China and Europe since the 1200s, turn out to be an ideal solution. They operate according to Newton's third law of motion: *For every action on one body, there is an equal and opposite force acting on another body*. The force used to expel high velocity gases from the back of a rocket nozzle pushes the rocket forward with an equal force, called thrust. The two bodies in this case are the gases and the rocket (Figure 37).

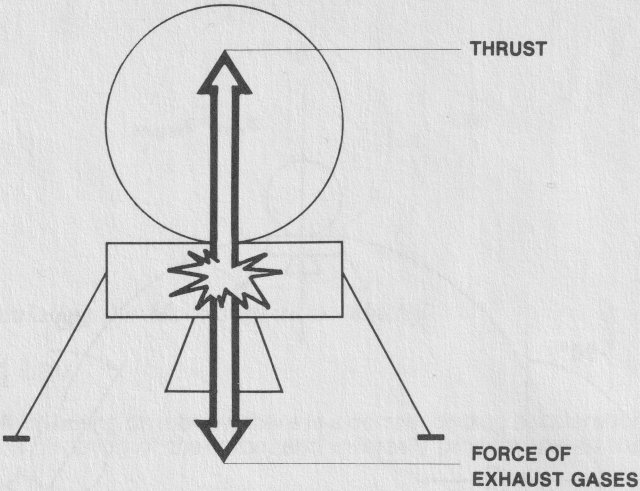


Figure 37: *LLV and the Third Law of Motion. Thrust equals exhaust force*

Newton's idea of launching an artificial satellite became a reality on October 4, 1957, when the Soviet Union launched Sputnik. Several months later the United States Army rocket team, headed by Wernher von Braun, sent Explorer I into orbit around the Earth. These first steps into space began the journeys of Mercury, Gemini, Apollo, the Space Shuttle, and will eventually culminate in space habitats like the DAKOTA and the Tranquility Base Mining Facility.

Newton's laws of motion and gravity form the basis of most of modern physics and theories of spaceflight. Newtonian dynamics can accurately predict the trajectories of spacecraft. The Viking orbiters were placed within a few kilometers of their designated orbit; Venera 8 was placed precisely on the sunlit side of the equatorial terminator of Venus; and Voyagers 1 and 2 were placed in exactly the correct entry corridor to be directed close to Jupiter and Saturn. Would-be space colonists must acquire a thorough understanding of Newtonian physics if they hope to become successful Tranquility Base LLV pilots.

Appendix D: THE MOON

	Moon	Earth
Equatorial Diameter (kilometers)	3476	12756
Mass (kilograms)	7.36×10^{22}	5.98×10^{24}
Mean Density (kilograms/meter^3)	3340	5522
Surface Gravity (meters/second^2)	1.67	9.81
Circular Velocity (kilometers/second)	1.68	7.91
Escape Velocity (kilometers/second)	2.38	11.2
Mean Surface Temperature (degrees Celcius)	120 (day) -150 (night)	22
Atmosphere	none	nitrogen/oxygen
Rotation Period	27.3 days	23.9 hours
Revolution Period	27.3 days	365.26 days

Mean Earth-Moon distance (kilometers) 3.80×10^5

Origin

Current theory holds that the solar system first came into being as a huge, whirling, disk-shaped cloud of gas and dust. Gradually the cloud collapsed inward. The central part became massive and hot, forming the Sun. Around the Sun, the remaining dust formed small bodies that rapidly collected together to form the large planets and satellites that we see today.

Measurements of the radioactive elements in meteorites indicate that the formation of the solar system occurred 4.6 billion years ago. There is chemical evidence from both lunar and terrestrial rocks that the Earth and Moon also formed at this time. However, the oldest known rocks on Earth are only 3.8 billion years old. Scientists think that Earth's older rocks have been destroyed by continuing volcanism, mountain-building, and erosion.

Moon rocks fill in some of this gap in time between the Earth's oldest preserved rocks and the formation of the solar system. The lavas from the dark basins are the Moon's youngest rocks, but they are as old as the oldest rocks found on Earth, with ages of 3.1 to 3.8 billion years. Rocks from the lunar highlands are even older. Most highland samples have ages of 4.0 to 4.3 billion years. Some moon rocks preserve traces of even older lunar events. Studies of these rocks indicate that widespread melting and chemical separations were going on within the Moon about 4.4 billion years ago, or not long after the Moon

had formed. Even more exciting is that a few lunar rocks seem to record the actual formation of the Moon, having an apparent age of 4.6 billion years.

The Moon formed as a part of our solar system, and has existed as an individual body for 4.6 billion years. It may have been formed by nearby particles left over after the Earth formed, or it may have originated elsewhere in the solar system and was eventually captured by the Earth. The first few hundred million years of the Moon's lifetime was so violent that few traces of this time remain. Almost immediately after the Moon formed, its outer layers were completely melted to a depth of several hundred kilometers. While this molten layer gradually cooled and solidified into different kinds of rocks, the Moon was bombarded by huge asteroids and other debris left over from the creation of the planets. Some of these asteroids were the size of small states, like Rhode Island or Delaware, and their collisions with the Moon created huge basins hundreds of kilometers across.

This catastrophic bombardment died away about 4 billion years ago, leaving the lunar highlands covered with huge overlapping craters and a deep layer of shattered rock. As the bombardment subsided, the heat produced by the decay of radioactive elements began to melt the inside of the Moon to depths of about 200 kilometers below its surface. Then, for the next half billion years, great floods of lava rose from inside the Moon and poured out over its surface, filling in the large impact basins to form the dark parts of the Moon that we see today.

As far as we now know, the Moon has been quiet since the last lava eruptions more than 3 billion years ago. Since then, the Moon's surface has been altered only by rare large meteorite impacts and by atomic particles from the Sun and other stars. The Moon has preserved features formed almost 4 billion years ago, and if men had landed on the Moon a billion years ago, it would have looked very much as it does now. The lunar surface now changes so slowly that the footprints left by the Apollo astronauts will remain clear and sharp for millions of years.

Features

The Moon's surface is characterized by a variety of features that make up the face of "the man in the Moon." Without using any special intruments we can see gray patches spotted across the Moon's face. With the aid of the telescope, we see shadows along the terminator (the line separating lunar day from lunar night) cast by circular craters, rugged mountain ranges, and deep winding canyons or rilles.

The gray patches are called maria, Latin for seas, that are vast plains covered by lava. Mare surfaces cover most of the near side of the Moon, but only 15 percent of the whole Moon. These lava plains have been given romantic names such as Mare Nectaris (Sea of Nectars) and Mare Tranquillitatus (Sea of Tranquility). Terrae, the bright areas of the lunar surface, are heavily cratered, rugged highlands.

The lunar landscape is covered by a gently rolling layer of powdery soil and rubble about 1 to 20 meters deep. This lunar soil has been built up over billions of years of continuous bombardment by large and small meteorites. Craters are formed when these meteorites hit the Moon. The impact shatters the solid rock, scatters material around the crater, and stirs and mixes the soil. This fine debris radiates from the crater in bright streaks, called rays. Tiny particles of cosmic

dust produce microscopic craters, while the rare impact of a large body may blast out a crater many kilometers in diameter. Lunar mountains are really the rims of vast craters, called basins, which in turn contain the lava plains. The largest of these, the Imbrium Basin, is about 1200 kilometers in diameter.

Composition

The Moon is made of rocks whose elements and minerals are quite similar to those of Earth rocks. No new elements are found on the Moon, and the most common lunar minerals are also common on Earth. Moon rocks are so much like Earth rocks that we can use the same terms to describe both.

All lunar rock are igneous, which means that they formed by the cooling of molten lava. No sedimentary rocks, rocks made out of particles deposited from the sea or air, have ever been found on the Moon. This indicates that the Moon probably never had water or atmosphere in its environment, but that it has been subject to rock melting, resolidifying, and fragmenting.

Moon rocks are made of the same chemical elements that make up Earth rocks, although in different proportions. Moon rocks contain more of the common elements calcium, aluminum, and titanium than do most Earth rocks. Rarer Earth elements, like hafnium and zirconium which have high melting points, are also more plentiful in lunar rocks. However, other elements, like sodium and potassium which have low melting points, are scarce in lunar material. Because Moon rocks are richer in high-temperature elements and contain less low-temperature elements, scientists believe that the material that formed the Moon was once heated to much higher temperatures than material that formed the Earth. Lunar rocks also contain silica - on Earth a useless waste product, but of value in space. They contain oxygen, too, chemically bound to the metals and silicon.

The lunar surface is disturbed by "moonquakes;" about 3000 of them are detected each year by instruments left on the Moon by Apollo. All of these disturbances are very weak by terrestrial standards, the larger moonquakes ranking only 0.5 to 1.3 on the Richter scale. The average moonquake releases about as much energy as a firecracker, and the whole Moon releases less than one-ten-billionth of the earthquake energy of the Earth. Moonquakes occur about 600 to 800 kilometers deep inside the Moon, much deeper than almost all the quakes on our own planet. This quake zone is at the bottom of a solid rock layer and at the top of a partially melted zone, indicating that parts of the Moon became hot enough to melt at some time in its past. Certain kinds of moonquakes occur at about the same time every month, suggesting that they are triggered by repeated tidal strains as the Moon moves in its orbit around the Earth.

A picture of the inside of the Moon has been put together from the records of thousands of moonquakes and meteorite impacts. The Moon is not uniform inside, but is divided into a series of layers just as the Earth is. The outermost part of the Moon is a crust, probably composed of calcium- and aluminum-rich rocks like those found in the highlands. For unknown reasons, the crust is about 60 kilometers thick on the near side, where the maria are, and over 100 kilometers thick on the far side. Beneath this crust is a thick layer of denser rock (the mantle) which extends down more than 800 kilometers. The deep interior of the

Moon is still a mystery. The Moon may contain a small iron core at its center, and there is some evidence that the Moon may be hot and even partly molten inside.

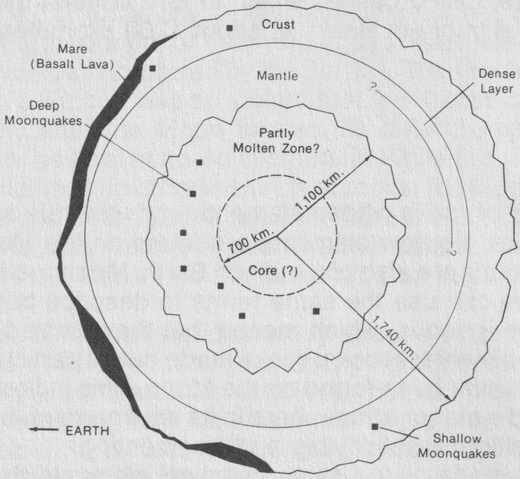


Figure 38: *Cross section of the Moon*

The Moon does not now have a magnetic field like the Earth's, and so the most baffling and unexpected result of the Apollo Program was the discovery of preserved magnetism in many of the old lunar rocks. One explanation for this discovery is that the Moon had an ancient magnetic field that was somehow "switched off" about three billion years ago.

Atmosphere

The Moon's sparse atmosphere is made up of argon (generated by radioactivity in the lunar crust), and hydrogen, helium, and neon (from the solar wind). But there is over a billion times less atmosphere on the Moon than there is on Earth. Because of this lack of atmosphere, the Sun's heat is not distributed across the Moon's entire sphere as it is on Earth. On the Moon, the temperature can be boiling hot in the sun, and freezing cold in a patch of shade just a few feet away. At lunar noon, temperatures can soar as high as 160 degrees Celcius, while night temperatures can plunge to -150 degrees Celcius. With no atmosphere to act as a shield, the Moon's surface is exposed to lethal doses of solar ultraviolet rays, X-rays, and charged particles.

Gravity

The effect of the Moon's gravitational force on the Earth can be seen in our ocean tides. When two bodies, such as the Moon and the Earth, are near each other, each exerts a gravitational force on the other. The side of the Earth facing the Moon experiences a stronger lunar gravitational force than does the far side of the Earth. This difference creates a stretching force that causes the oceans' surfaces to bulge on the Earth's near and far sides. Similarly, the effect of the

Earth's gravitational force on the Moon causes the lunar surface to bulge along its equator.

Gravity also affects the shape of space. It produces hills and valleys that are as important to space colonists as Earth's topography is to terrestrial settlers. Every massive body, such as the Earth and the Moon, sits at the bottom of a gravitational well. The more massive the body, the deeper is this valley or well. The Earth's gravitational well is 22 times deeper than that of the Moon. Objects can be more easily lifted into space from the Moon than from Earth.

Gravity shapes space in more subtle ways as well. The Earth-Moon system has shallow valleys around what are known as Lagrangian libration points (Figure 39). There are five of these points, and they arise from a balancing of the gravitational attractions of the Earth and Moon with the centrifugal force that an observer in the rotating coordinate system of the Earth and the Moon would feel. The principle feature of these locations in space is that a body placed at one of these points will maintain a fixed relation with respect to the Earth and the Moon as the entire system revolves around the Sun.

The points labeled L_1, L_2, and L_3 in Figure 39 are saddle-shaped valleys. If a body located at one of these points, such as a space colony, is displaced perpendicularly to the Earth-Moon axis, it slides back to the axis, but if it is displaced along the axis it moves away from the libration point indefinitely. For this reason these are known as points of unstable equilibrium. L_4 and L_5, on the other hand, are bowl-shaped valleys. A body displaced in any direction returns toward the point. These are known as points of equilibrium. They are located on the Moon's orbit at equal distances from both the Earth and the Moon.

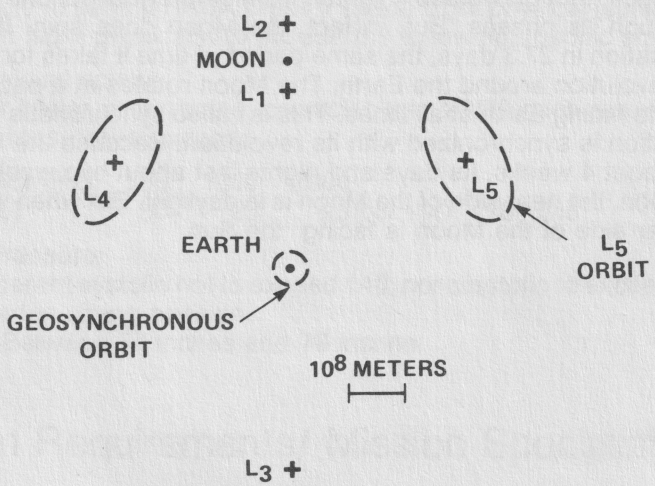


Figure 39: *Earth-Moon libration points*

Motions and Dimensions

Celestial phenomena have been important to man since the beginning of time. The stars were his guideposts in unfamiliar territory, and the motions of the planets provided cycles on which time measurements were based. Cycles of the

Moon divided the year into twelve approximately equal periods, called months, of 29.5 days each. This regular pattern allowed man to make calendars with which he could predict harvests.

As seen from Earth, the Moon looks like a flat disk. During the course of a month, the Moon passes through eight distinct phases, from new moon (the thinnest crescent) to full moon (fully illuminated disk) and back to new moon. The imaginary line that separates the lighted side from the unlighted side is called the lunar terminator. As the Moon passes through its phases, the lunar terminator changes its curvature. This fact indicates that the Moon is a sphere rather than a flat disk. Lunar visits and observations have proven that the Moon is not a perfect sphere, but slightly egg-shaped, with the small end of the egg pointing towards the Earth and the larger end pointing away from us.

Relative sizes and angles of the Moon's and the Earth's shadows indicate that the Moon is smaller than the Earth and the Earth is smaller than the Sun. The Moon's diameter is 3476 kilometers (2160 miles) across, about one-fourth the size of Earth. Its surface area is 101 million square kilometers (the United States covers 5.7 million square kilometers).

By bouncing laser beams off reflectors placed on the Moon by Apollo astronauts, we can measure variations of the Earth-Moon distance to within a few inches. The Moon maintains an average distance of about 384,632 kilometers (238,857 miles) from the Earth. This distance varies throughout the Moon's revolution around the Earth because its orbit is slightly elliptical.

Although we can see evidence that the Moon revolves around the Earth, we do not see the Moon spin (rotate around its axis). From day to day we see the same lunar face, though we see it lighted from different directions as the Moon passes through its phases. But, in fact, the Moon does spin. It makes one complete rotation in 27.3 days, the same period of time it takes for the Moon to make one revolution around the Earth. The Moon rotates at a pace that keeps the same side facing Earth at all times. This is called synchronous rotation. The Moon's rotation is synchronized with its revolution. Because the Moon's rotation takes about 4 weeks, its days and nights last about two weeks. When we see a full moon, the near side of the Moon is in daylight. But when we see a new moon, the far side of the Moon is facing the Sun.

Appendix E: PILOT and MISSION SPECIALIST QUALIFICATIONS

Minimum Requirements/Pilots

Pilot candidates are required to have a bachelor's degree from an accredited institution in engineering, biological or physical science, or mathematics. An advanced degree or equivalent experience is desired. Quality of academic preparation is important. To meet the minimum qualifications, an applicant must also have at least 1,000 hours pilot-in-command time in high performance jet aircraft. Flight test experience is highly desirable. The pilot applicant must be able to pass a NASA Class 1 space flight physical (similar to military and civilian flight physicals) to include the following specific standards:

Distant visual acuity:
20/50 or better uncorrected; correctable to 20/20 each eye.
Hearing loss not to exceed:

Frequency (Hz)	500	1000	2000
Loss (db)	30	25	25 per ISO, 1964 Std.

Blood Pressure:
Preponderant systolic not to exceed 140, nor diastolic to exceed 90 mm Hg, measured in sitting position.
Height: Between 64 inches and 76 inches.

Minimum Requirements/ Mission Specialists

Mission Specialist candidates must have a bachelor's degree from an accredited institution in engineering, biological or physical science, or mathematics. Degree must be supplemented by at least three years related experience. An advanced degree is desired and may be substituted for the experience requirement (masters' degree=1 year, PhD degree=3 years). Quality of academic preparation is important. Candidates must pass a NASA Class II space flight physical (similar to military and civilian flight physicals) to include the following specific standards:

Distant visual acuity:
20/100 or better uncorrected; correctable to 20/20 each eye

Hearing loss not to exceed:

Frequency (Hz)	500	1000	2000
Loss (db)			
Better ear	30	25	25
Worse ear	35	30	30 per ISO, 1964 Std.

Blood Pressure:
Preponderant systolic not to exceed 140, nor diastolic to exceed 90 mm Hg, measured in a sitting position.
Height: 60 inches to 76 inches.

Appendix F: USING Lunar Explorer IN THE CLASSROOM

Lunar Explorer can be a valuable tool in the study of astronomy, physics, and space sciences. It provides an interactive setting in which students can explore some of the dynamics of spaceflight. This simulation can be used in conjunction with or subsequent to classroom instruction in basic scientific principles and concepts. As a model of real-world phenomena, *Lunar Explorer* can make abstract concepts more concrete, provide a foundation for future study, and inspire interest in learning about science.

Topics for Study

Lunar Explorer demonstrates the application of concepts in several subject areas. This program can generate general discussions about spaceflight as well as focus classroom investigation on the specifics of spaceflight dynamics. Students can compare simulations and their real-world counterparts while examining the general characteristics of simulations.

Listed below are some of the subject areas addressed in *Lunar Explorer*, along with suggestions for additional related topics.

Dynamics

Lunar Explorer is a model of dynamics. When experimenting in the *Lunar Explorer* environment, students confront and must learn to master Newton's three laws of motion. You can select appropriate training exercises described in this manual as specific experiments in inertia, acceleration and mass, and action-reaction. These simulations can provide a foundation for understanding hands-on laboratory experiments using equipment such as pulleys and weights.

Gravity

Lunar Explorer can be used as a laboratory for conducting simple experiments in Newton's law of gravity. For example: Determine the Moon's acceleration due to gravity. Have students bring the lunar lander to a low altitude. Then turn off the engine and record the altitude (**ALT**) and the vertical velocity (**VELZ**) given on the

control panel. Altitude and vertical velocity should be recorded again at another point during free fall. The Moon's acceleration due to gravity can be determined by using the formula:

$$\text{ACCgrav} = \frac{\text{VELZinitial}^2 - \text{VELZfinal}^2}{2 \times (\text{ALTinitial} - \text{ALTfinal})}$$

Vectors

Vectors, quantities having both magnitude and direction, are used to express many laws of physics. On paper, they are represented by arrows. The direction of the arrow represents the vector's direction, and the length of the arrow represents the vector's magnitude. The total effect of two vectors is represented by adding the vectors, that is, drawing the second vector with its tail at the head of the first vector. Their sum is a third vector beginning at the tail of the first vector and ending at the head of the second vector.

Thrust is a vector quantity; its direction determined by pitch and roll, its magnitude by engine thrust. In piloting the *Lunar Explorer* spacecraft, students gain an intuitive understanding of vectors and vector addition. This knowledge can be made explicit by classroom discussion of vectors and assignments in diagramming thrust and gravity vectors on graph paper.

History of Spaceflight

In recreating some of the sights and dangers of spaceflight, *Lunar Explorer* can add excitement and relevance to a discussion on the history of spaceflight. Topics that you might wish to cover include spaceflight in early fiction, experiments in rocketry, the first satellites, space probes, sub-orbital and orbital flights, the Apollo program, Skylab, the Space Shuttle, and NASA's designs for the future.

Space exploration as a scientific effort can not be understood completely when it is divorced from politics or national goals. An additional activity you might wish to pursue with your class is a discussion of the political and social factors that led to the decision to go to the Moon.

Lunar Studies

Lunar Explorer recreates the Moon's dimensions, gravity, surface features, and views of Earth. These aspects of the simulation can illustrate discussions of the causes of craters, and the synchronous rotation of the Moon (which keeps the same side of the Moon facing Earth). Classroom discussion can go beyond the boundaries of the computer to investigate the Moon's origin and history, composition, other surface features, motions, and gravitational effects on Earth. (See Appendix D: The Moon.)

Solar System Exploration

Study of the Moon is often the first step in exploring the solar system in the classroom. *Lunar Explorer* can be used as an introduction to the solar system. A survey of the solar system can cover configuration, revolutions and eclipses, comparisons of the planets and satellites, and the possibilities of extraterrestrial life.

Space Habitats

Space colonization, mining, and manufacturing is the environment in which the *Lunar Explorer* simulation becomes meaningful on a grand scale. NASA has developed detailed designs for space platforms, stations, colonies, and other structures that could be constructed within the next 50 years. Classroom discussion of space habitats can be a lead-in for the study of space construction, the physiological and psychological considerations of space habitat design, space nutrition and medicine, solar energy, and Earth applications for space technology.

Problem Solving Skills

Lunar Explorer can help to develop problem solving skills which underlie all traditional instruction. This simulation encourages active problem solving by making the student responsible for discovering answers through inductive thinking. To solve any new piloting problem, the student must observe changes in the scene through the "spacecraft window," gather data from the control panel, form hypotheses about the effects of possible actions, and experiment with the vehicle controls.

Using Models

Simulations can teach students to use models critically and effectively. Through the model of the LLV-Moon system presented in *Lunar Explorer*, students can investigate what makes a system work and how its components interact. By noting the control panel readouts as the lander travels under its own inertia, students can observe the dynamics of systems and the relationships between variables over time. By manipulating different variables such as thrust and pitch and noting the resulting effects on the LLV's motion, students can learn the relationship between their participation in a model and the rules that govern the behavior of the model's elements.

Classroom Implementation

Using computer simulations successfully in the classroom does require some preparation. Spend some time with the simulation to determine how *Lunar Explorer* should be integrated into your lesson plan. The training exercises detailed in this manual are good examples of the sorts of activities that you can assign to your students. Select activities that best fulfill your lesson's objectives

and then test *Lunar Explorer* with several students before using it with the entire class.

When presenting *Lunar Explorer* to the entire class, take your students on a trial run through the program. Make sure that everyone knows how to use the keyboard or joystick controls. Discuss potential problems and possible solutions with the class before using the program. Also, provide hints on strategies for using the simulation successfully. For example, you might suggest that students change only the lander's pitch and see what effect that has on the instrument readout.

If you have only one computer available and study time is short, you may want to use the program as a class activity. Raise important questions and have your students offer their observations and alternative solutions to questions posed by you.

If several computers are available or if you plan to use *Lunar Explorer* over several days, let small groups work together on the computer. Because *Lunar Explorer* requires continual interaction by the player, students should be assigned to the computer as individuals or in groups of no more than five.

When working with small groups, assign a specific area of responsibilty to each student in a group. For example, one student might be responsible for choosing the flight course, another student for piloting the craft, and a third for recording the results. Define some rules and guidelines with each group: How will you decide who gets which role? What will the group do if the pilot accidentally crashes the ship or goes off course?

After the class has completed the simulation, you might want to hold a "debriefing" session. Allow your students to discover the connection between the simulation and reality, and to relate what they've learned to other classroom activities. Some useful questions are: What procedures did you try, and what happened? What obstacles did you encounter, and how did you overcome them? What did you learn? What strategies did you use, and which ones worked best? What if you had tried something else?

Supplementary Activities

The following activities can be used with students not working at the computer. They also can be given as homework or extra credit assignments. These activities vary in complexity, need for teacher supervision, and expense.

- List some of the forces we encounter on Earth. Which ones are true forces? Which are action-reaction pairs?
- Prepare a timeline of the history of rocketry and spaceflight
- Research spaceflight in fact and fiction
- Compile a list of supplies that a stranded astronaut might find useful on a long trek back to the safety of a Moon base. Which of these items would an Earth-bound traveler find necessary? Which items would be useless on Earth?
- Collect images of the Moon taken by spacecraft and compare them with pictures in pre-Space Age books
- Compare old ideas about the Moon with new information that has been gathered during lunar visits by Pioneer, Surveyor, and Apollo

- Compile a list of consumer products found in everyday life that have come out of the space program
- Investigate local uses of solar energy
- Read a current science fiction novel or see a science fiction film that involves large space structures. Write a critique of the hardware created for the story
- Read a biography of a rocket or space pioneer. Write a book report
- Research space and solar power stations
- Research environmental elements that must be considered in designing space suits, capsules, laboratories, and stations
- Research current space propulsion and new propulsion systems that would make long duration flights into deep space possible
- Examine the Moon with a telescope. Make sketches of craters, ray systems, mountains, and rilles
- Purchase solar cell kits from a local hobby shop, electrical supply store, or other retail outlet. Build and operate cell-powered models or lights
- Use a Behr's free-fall apparatus to measure the gravitational attraction the Earth exerts on a small body. Plot a graph of average velocity versus time

Additional Study Materials

NASA educational resource centers make curriculum materials available to teachers. Lists of NASA Publications and NASA films are available from each center's Educational Services Office. Teachers, Grades 6-12, interested in becoming certified to use the Lunar Sample Educational Packet should contact the center's Educational Programs Office. Each center serves a specific geographic area. Check the list below for the center nearest you:

Ames Research Center
Moffett Field, CA 94035

Dryden Flight Research Center
Edwards Air Force Base, CA 93523

Goddard Space Flight Center
Greenbelt, MD 20771

Johnson Space Center
Houston, TX 77058

John F. Kennedy Space Center
Kennedy Space Center, FL 32899

Langley Research Center
Hampton, VA 23665

Lewis Research Center
Cleveland, OH 44135

George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

National Space Technologies Laboratories
Bay St. Louis, MS 39529

The Lunar Science Institute in Houston, Texas, can provide information about lunar science and about data resources that are available for educational purposes. In particular, the Institute maintains lists of available books, articles, photographs, maps, and other materials dealing with the Moon and the Apollo missions. For further information contact:

Lunar Science Institute
Data Center, Code L
3303 NASA Road #1
Houston, TX 77058

The L5 Society is an international organization committed to actively promoting space development. For a list of local chapters or more information about their programs, write to:

L5 Society
International Headquarters
1060 East Elm
Tucson, AZ 85719

Appendix G: SOURCES and ADDITIONAL READING

Sources

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CUSTOMER SERVICE and WARRANTY INFORMATION

Customer Service

If you have questions about using an Electric Transit program after reading the manual, please call us at **805/373-1960**. We will be happy to help you Monday through Friday, 9:00 AM to 5:00 PM Pacific Time.

Warranty

Electric Transit, Inc. warrants to the original consumer purchaser that this Electric Transit product shall be free from defects in workmanship and materials for a period of 90 days from the date of purchase. Electric Transit will replace free of charge any Electric Transit product found to be defective during this warranty period. Please call our customer service number (**805/373-1960**) before returning any product to Electric Transit to determine if it is a hardware or a software problem. Have the model of your computer, and the title and version number of the program (found on the program title page) handy when you call. By returning your owner registration card, you will speed up the replacement process, should the need for replacement arise.

Back-up Copies

One back-up disk per product may be purchased directly from Electric Transit for $12.00 if, and only if, your owner registration card is on file at Electric Transit.

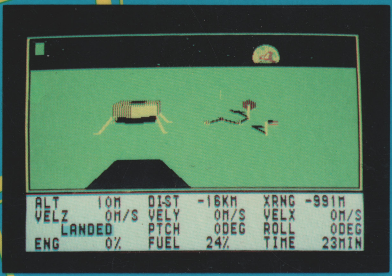
Disk Replacement After Warranty Period

If you need to replace your Electric Transit program disk after the 90 day warranty period has expired, Electric Transit will replace it for $12.00 if, and only if, your owner registration card is on file at Electric Transit and you send in the damaged or defective disk.

F O R · A G E S · T H I R T E E N · T O · A D U L T

LUNAR EXPLORER

A Space Flight Simulator



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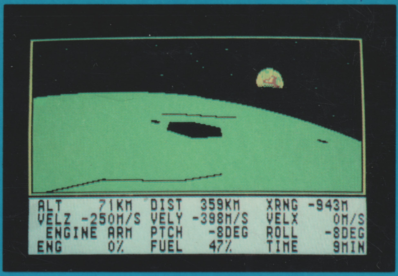

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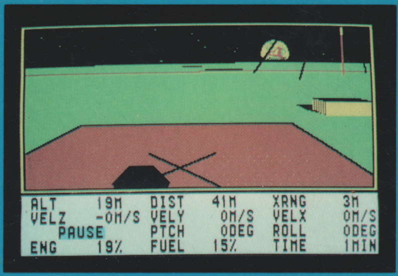

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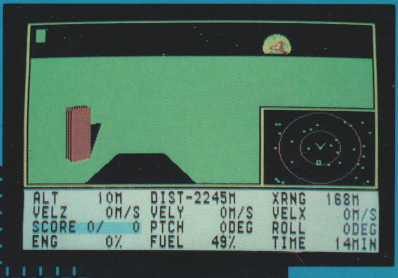

E

Screen photos from IBM version

A. The Apollo II landing site lies just beyond Tranquility Base.

B. Hover above the Base and get a bird's eye view of the mining facility.

C. Achieve lunar orbit and observe landmarks from high above the Moon's surface. Then...

D. Drop down to an altitude of 19 meters and fly over Tranquility Base.

E. Locate lunar ore canisters, load them, and return...before you run out of fuel.

Lunar Explorer is a real-time simulation of lunar flight from orbit to Moon landing from the pilot's point of view. Fast reflexes, split second timing, and a thorough knowledge of the laws of gravity and motion are all that stand between your fragile craft and the hazardous lunar terrain. Explore the Moon; investigate rilles and craters. Marvel at constellations and the Earth rising above the Moon's horizon.

Join the Space Colonization Project and become part of the future.

Apple version requires 48K, one 16-sector disk drive. IBM & compatibles version requires 128K, color graphics card, one disk drive

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